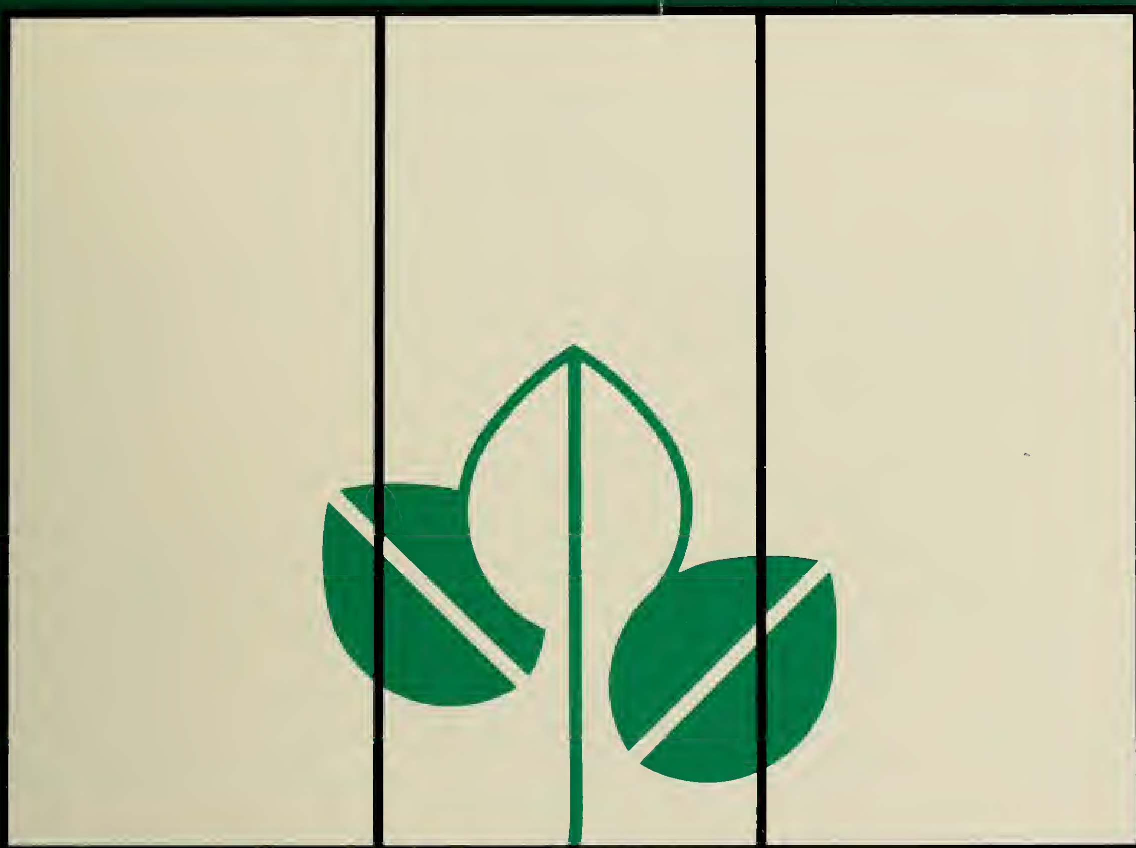

Solar greenhouses for commercial growers

Agriculture Canada

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Solar greenhouses for commercial growers

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Introduction

The North American greenhouse industry is relucant to adopt solar heating as a measure for reducing energy costs. The technology is viewed as being too expensive, complex, and unreliable. However, solar greenhouse research sponsored by Agriculture Canada has produced promising results.

Successful solar greenhouse studies have been done at the Agriculture Canada Research and Plant Quarantine Station in Saanichton, B.C., located 48°37′ latitude north, 25 km north of Victoria. The experimental greenhouses receive approximately 2100 hours of bright sunshine on an annual basis. This is slightly above the average of 2035 hours for 38 different locations throughout the southern part of Canada.

Three different solar greenhouses have been constructed at the research station. The first greenhouse is a 10.8 m × 19.2 m glass-covered conventional even-span gable greenhouse. It has an earth thermal storage (ETS) heating system and is equipped with thermal screens. The second greenhouse is a 6.4 m × 18.3 m shed-type structure. It is one half of a conventional prefabricated glass-on-galvanized steel greenhouse with the north roof eliminated and the north wall insulated. This greenhouse is equipped with an internal solar collector and a rock storage heating system as well as thermal screens. The third greenhouse is a prefabricated polyethylene quonset house, measuring 8.84 m × 15.24 m. This greenhouse is heated exclusively by an ETS solar heating system.

This publication is intended to supply commercial growers with some basic information on solar heating. It examines some of the different methods of storing excess solar energy and provides guidelines on the design, cost effectiveness, and reliability of solar greenhouses that are either new structures or retrofitted conventional ones. The guidelines are based solely on findings obtained from the experiments conducted at Saanichton, B.C.

The information will help the grower to decide whether or not to seriously consider installing solar systems. However, an agricultural engineer should be consulted before a final decision is made to proceed.

Climatic Considerations

For obvious reasons, climate is of special importance to the proper function of a solar greenhouse. The four weather elements to be considered are sunshine, temperature, snowfall, and wind.

Some of the weather records of representative weather stations across Canada are provided in Appendix A. Mean values of daily global solar radiation and hours of bright sunshine are listed in Tables 1 and 2, respectively. Temperature data are presented in Table 3 and snowfall records are given in Table 4. Finally, Table 5 provides information concerning mean wind speed and prevailing direction (Canada Atmospheric Environment Service 1982*a,b,c,d,e*). For bright sunshine and windspeed, there are a few instances where data are unavailable for the station listed. In those cases, data from the nearest reporting station (not identified) have been supplied. For locations not listed, the grower is directed to contact the nearest Environment Canada Weather Office to obtain representative weather data.

Most commercial operators purchase prefabricated greenhouses with structurally engineered frames consisting of galvanized steel and aluminum. However, if any readers wish to plan and build their own greenhouses, they are advised that extreme weather records should not be used, otherwise the structure, heating systems, and so forth will be overdesigned. The greenhouse must be designed in accordance with the National Building Code of Canada. Before beginning construction, readers should consult additional literature concerning greenhouse design standard guidelines (American Society of Heating, Refrigerating and Air-Conditioning Engineers 1981; National Greenhouse Manufacturers Association 1981; Flowers Canada Inc. 1983).

Given the wide variety of climatic conditions, greenhouse structures, crop requirements, and so forth encountered in Canada, it is difficult to make recommendations concerning the suitability of a particular location for solar greenhouses. The solar designs tested at Saanichton have not been evaluated in other regions of the country. However, the following preliminary guidelines are offered with respect to climate.

Sunshine

The availability of solar energy is influenced by season, time of day, atmospheric conditions, and surface orientation and placement (Jackson 1983). Normally, temperature conditions and sunshine data must be considered when determining the potential for solar heating (see following section for discussion). However, the successful operation of a solar greenhouse is

highly dependent upon the mean daily amounts of global solar radiation and number of hours with bright sunshine. If the solar radiation levels received at a location are below average for Canada, solar heating is probably not feasible.

The critical months to consider are March through October; during the winter period of November through February virtually all the solar radiation trapped inside a greenhouse is required for daytime heating demands (Blom et al. 1982; Jackson 1983).

The results of experiments at Saanichton have been used to establish minimum levels of sunshine necessary for solar heating. If the sum of the values of mean daily global radiation for each month in the March–October period exceeds 125 MJ/m^2, the location may be suitable for solar greenhouses (Table 1). In the absence of global radiation data, the total number of hours with bright sunshine in the same period should be studied. Solar heating may be feasible if the total exceeds 1500 hours (Table 2).

Temperature

After available sunshine has been considered, temperature becomes the most critical climatic factor influencing the operation of solar greenhouses. In cold climates, low winter temperatures increase the rate of heat loss from the greenhouse interior as well as from the underground thermal storages. During sunny days, excess solar energy does not become available for storage if cold outside temperatures produce excessive heat losses. If the ground surrounding the thermal storages is also very cold, heat losses from the storages make it difficult to maintain adequate reserve heat levels. It is important to note that even if the thermal storages are much warmer than the surrounding ground, the stored heat becomes useless if the storage temperature is below the interior nighttime set point.

The procedure for calculating heat losses and net daytime solar heat gains is well established (National Research Council of Canada 1981*b*; Blom et al. 1982; Darby 1982; Kadulski et al. (date unknown); Roberts et al. 1985). Table 3 provides the annual heating degree-days for different Canadian locations. One degree-day is equivalent to a daily mean temperature one degree below 18°C for a duration of 24 hours. As the number increases, proportionally greater amounts of heat are required to maintain the greenhouse environment at 18°C. If the available solar radiation is sufficient in comparison to the heating load during the growing season between March and October, solar heating may be economical for greenhouses.

To quantify the relationship between solar radiation and heat load, the ratio of the sums of the values of mean daily global radiation to number of degree-days for each month in the growing season must be examined. If this ratio exceeds 0.08, solar heating may be feasible for that particular location.

For example, this ratio for Edmonton, Alta., one of the sunniest locations in Canada, is 131.82 MJ/m^2 of mean daily global radiation to 2425 degree-days. After division, this results in a value of 0.054. Consequently, Edmonton is not suitable for solar greenhouses because of its cold nights in the spring and fall. However, Toronto, Ont., has a ratio of 135.86 MJ/m^2 to 1591 degree-days, which equals a value of 0.085. Therefore, a properly designed solar greenhouse may be economical there.

If global daily radiation data are not available for the location in question, the ratio of hours of bright sunshine to number of degree-days should be evaluated. In this situation, solar heating should be seriously considered if the ratio exceeds 0.8. For example, in Vancouver, B.C., the total number of hours of bright sunshine during March–October is 1669, whereas the number of degree-days is 1372. This results in a ratio of 1.22, indicating that a preliminary design evaluation should be done. Readers are cautioned that the second method is less accurate and not quite so conservative.

Snowfall

A greenhouse structure must be designed to withstand the weight of snow accumulation, in accordance with the National Building Code of Canada. The design snowload is calculated on the basis of a location's maximum 24-hour snowfall (Table 4).

Readers may be contemplating using solar heat to extend the growing season in a structure that would otherwise be unheated. In such instances there will be no heat available for melting. Therefore, the roof must be built to withstand design accumulations or, alternatively, the roof must be pitched at a steep enough angle to ensure that snow will slide off and the sidewall height must then be sufficient to allow snow to clear the roof. The grower is directed to Flowers Canada Inc. (1983) and National Greenhouse Manufacturers Association (1981) for a thorough discussion of this subject.

Wind

A greenhouse location with constant exposure to high wind speeds can result in increased heat loads of up to 25% annually. Greenhouses are not generally recommended in exposed locations where mean wind speeds in excess of 25 km/h are encountered during any of the winter months (Table 5). Exposure can be reduced and heat losses cut by 5% to 10% by erecting a windbreak. The windbreak must not shade the growing area, an especially critical point with solar greenhouses. For guidelines on the construction, costs, and benefits of windbreaks, see Roberts et al. (1985).

Site Selection

Several factors must be considered when selecting a site for any commercial greenhouse operation. The location should be relatively flat, because a level grade must be established before construction begins. The site should provide good drainage and the space and orientation that may be required for future expansion. Distances to markets and the condition of interconnecting roads are also important considerations. Obviously, it is essential that there be a considerable degree of exposure to the sun. When presented with the choice, it is desirable to have exposure to the early morning sun as opposed to the late afternoon or evening sun. Plants become photosynthetically active as soon as they receive their first light of the day. However, on long, hot days, some plants may slow photosynthesis in midafternoon due to high water loss from rapid transpiration and other stress-related factors. In low-lying, sheltered areas such as frost pockets the early morning sun is critical for reducing heat loads and burning off fog.

When selecting a site for a solar greenhouse, special attention must be given to the topography, the water table, and the greenhouse orientation.

Topography

The site must be virtually free from obstructions that could otherwise block incoming solar radiation. If obstructions cannot be removed, the percentage of daily sunshine being lost must be determined, using the procedures and charts contained in Appendix B. If the percentage of blocked sunlight exceeds 15% during any of the months in the growing period of March–October, then the site is probably not suitable for solar heating.

The solar heating systems discussed here are designed to use underground thermal storages installed to depths of about 1 m. The cost projections for the economic feasibility studies assume that a trencher, or backhoe, can be used to install piping or rock storages. These cost projections would rise dramatically if it became necessary to blast rock in order to install the solar systems and could seriously influence the economic potential of any project. Therefore, it is critical to ensure that no bedrock lies closer to the surface than 1 m below site grade. Large boulders are also likely to cause problems. A silty loam is the ideal material to contend with, but few problems should occur with any type of free and loose material.

Water table

Locating thermal storages underground also makes the water table an important site consideration. If groundwater can migrate transversely across

a storage, the collected heat will be lost very quickly. This can be prevented by installing drainage around the entire greenhouse at a depth of 0.5 m below the thermal storage.

It is recommended that the drain pipes be placed in drain rock or gravel. The rock material surrounding the pipes should extend from 30 cm below grade down to 10 cm beneath the pipes. If the heat storage system is installed against the north wall the water table can be as high as 1 m below grade.

Greenhouse orientation

The ETS solar greenhouse design is adaptable to any orientation. However, other designs, including the solar shed-type configuration, only function propely in an east–west alignment.

Most greenhouse operations are located in the southern part of Canada (43°–50° northern latitude). In some areas, winter light levels can be a limiting factor. For single-span greenhouses an east–west orientation is generally preferred over a north–south orientation because this maximizes light levels in winter and reduces light levels in summer, thereby decreasing ventilation requirements. This advantage of an east–west alignment becomes more evident with increasing distance from the equator. Furthermore, if a grower decided to insulate the north wall in a single-span greenhouse, the reduction of heat losses would be much greater with an east–west orientation.

In multispan, gutter-connected greenhouses, the light transmission advantage of an east–west alignment is more than offset by fixed areas of shading produced by the gutters. For this reason, multispan, gutter-connected greenhouses are almost always oriented north–south. This orientation allows gutter shadows to move from west to east across each bay during the day.

Earth Thermal Storage Solar Heating System

Description

An ETS solar heating system (Fig. 1) uses the soil beneath the floor as heat storage material. As the greenhouse air temperature rises above the set point, hot air that collects near the peak is drawn through a network of buried pipes below the floor, using a large electric fan. As heat is transferred to the pipes they increase in temperature and transfer the heat to the surrounding soil. The cooled and dehumidified air is then blown back into the greenhouse. Therefore, although the ETS system is collecting heat it is also functioning as a first-stage cooling system. The storage becomes fully charged when the temperature of the air exiting the pipes is equal to or greater than the temperature of the air entering the pipes. The solar fan should not be operated whenever the earth storage is at maximum temperature, because then the electrical input energy is wasted. A second-stage cooling system must be provided for these occasions and for whenever the ETS system has insufficient cooling capacity to maintain the set point temperature.

When the inside air temperature falls below the set point, heat can be released from the storage if the soil is at a higher temperature. Most of the heat is released into the greenhouse by circulating the inside air through the pipes again. The air absorbs the heat through the pipe sidewalls before it is returned to the greenhouse. A small portion of the stored heat is transferred by conduction to the interior through the greenhouse floor.

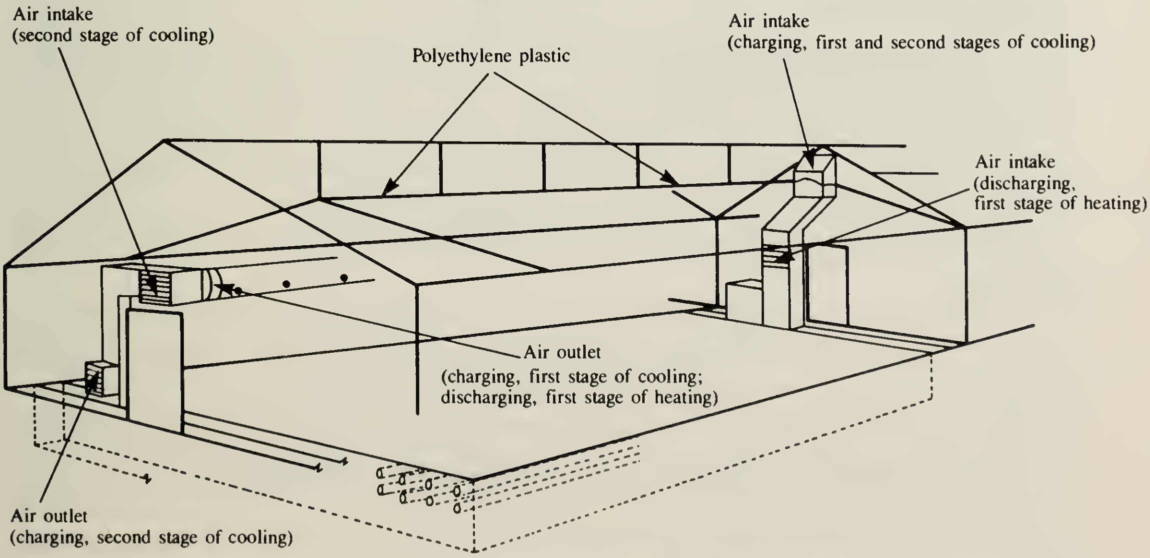


Fig. 1. *An ETS heating system design for gutter-connected, even-span gable greenhouses.*

The storage is discharged completely when the temperature of the air exiting the pipes is equal to or less than the air temperature inside the greenhouse. The solar fan should not be operated when the storage is empty because this wastes electrical power. If a minimum set point temperature must be maintained, a backup heating system is required. It should be sized for the winter design heat load, because no solar heat would be available under those conditions. The backup heating system can be used in conjunction with the ETS system whenever solar heat is available, but it is insufficient to maintain the set point temperature.

The efficiency of the solar fan can be increased by enabling it to provide forced-air ventilation in the greenhouse as a second stage of cooling. If an air inlet with a motorized shutter is installed at the opposite end of the greenhouse from the fan, fresh air will be drawn through the greenhouse interior. The air will then enter the air intake, pass through the fan, and be forced back through the pipes. The ETS system will serve as a heat exchanger to remove heat from the ventilated air before it is discharged outside through a motorized outlet.

The overall efficiency of the ETS system can also be increased by raising the air inlet temperature during charging. This can be accomplished by extending a single layer of clear polyethylene film along the peak, creating a horizontal zone of relatively undisturbed air. The plastic should extend longitudinally from the gable adjacent to the fan inlet to a point about 1 m from the opposite gable. This would leave a gap for air intake. The separation distance between the roof cover and the plastic should also be about 1 m. Readers are cautioned that this measure significantly reduces the effectiveness of the ridge ventilators, because the film blocks the free movement of air to the crop.

If thermal screens are installed in the greenhouse, a single air inlet can be installed underneath. However, a second daytime air inlet should be installed above the screens if temperatures in the peak are at least 3°C higher than below the screens.

Applications

ETS systems do not depend on any type of solar collector to accumulate heat. The greenhouse itself serves as a solar collector, utilizing both direct beam and scattered diffuse solar radiation transmitted through every surface of the structure. Consequently, an ETS system can be installed in any greenhouse, regardless of orientation or structural configuration. A north–south alignment enhances summertime performance, since more light enters the structure.

For even-span gable greenhouses, the ideal roof slope for maximum light transmission is about 10° lower than latitude. For example, if the greenhouse location is at a latitude of 49°, the ideal roof slope would be 39°. However, the high peak on such a greenhouse would require costly construction and operating expenses. Most greenhouses constructed for commercial use have a roof slope of 26° or 32° (Mastalerz 1977). At a reasonable cost, this provides for snow slippage, a high level of light transmission, and prevents condensation drips.

The type of material covering the structure is not critical because the inside surfaces absorb either beam or diffuse light and subsequently transmit heat back into the greenhouse air. Glass transmits more light than other materials but offers little resistance to heat loss. Double polyethylene films do not transmit as much light, but their resistance to heat transfer is much higher. Since heat losses through the covering are lower, a greater portion of the accumulated excess heat is available for storage. Ideally, the covering should provide both high light transmittance and high resistance to heat loss. Some double layer acrylic materials offer both advantages but at a very high cost.

Double-polyethylene quonset greenhouses are currently the most inexpensive and simplest greenhouses to construct. The galvanized steel arches are supported by concrete friction footings and the end walls are usually framed with 2 × 4s to support a sliding door. Growers who are just starting their commercial greenhouse operations often initially build quonset greenhouses because of their low capital and heating costs.

ETS systems are compatible with this type of structure, especially if they are made as inexpensively as possible (Fig. 2). The ductwork above the ground can be eliminated by extending the pipes up out of the ground and turning the ends in toward the greenhouse so that the exhaust air is blown over the crop.

In moderate climates, an ETS system in a double-polyethylene quonset greenhouse can maintain a frost-free environment unless temperatures fall below -10°C. Such a greenhouse can be an inexpensive shelter for overwintering young nursery stock. The ETS system can also extend the growing season in an unheated tunnel. When backup heating systems are installed, the ETS system can provide cost effective energy savings.

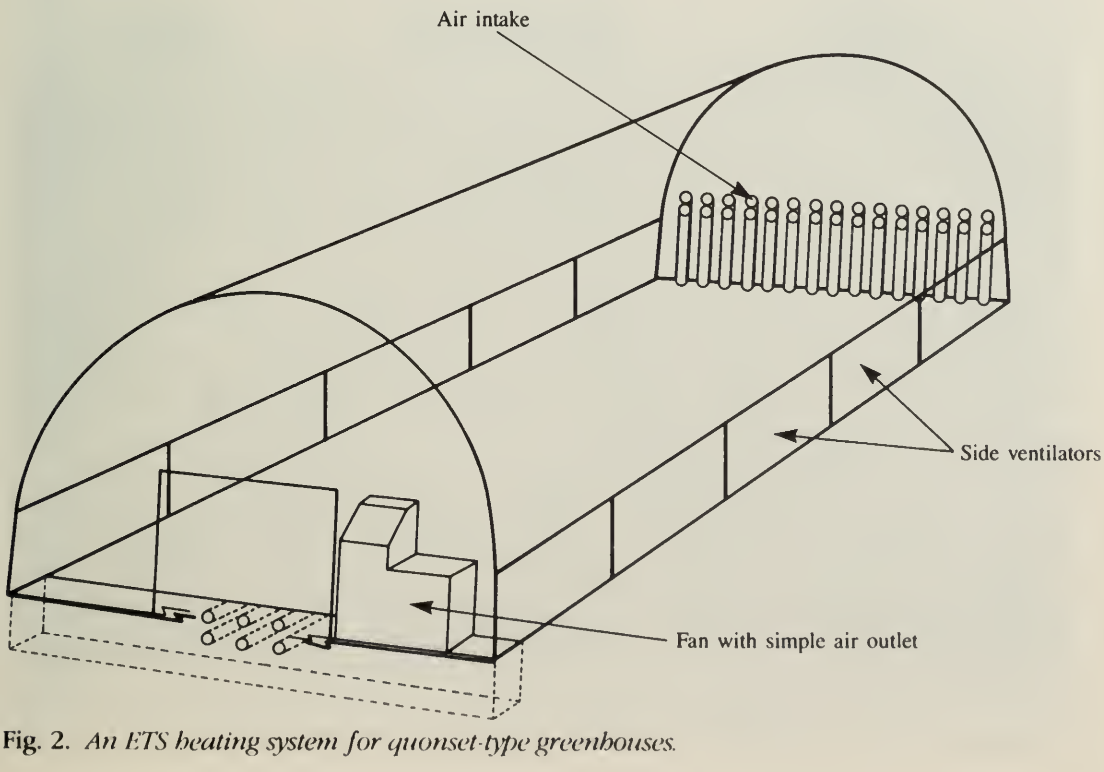


Fig. 2. *An ETS heating system for quonset-type greenhouses.*

Obviously, it is more simple and less expensive to install an ETS system in the ground before the greenhouse is erected. However, an ETS system can be easily retrofitted into any greenhouse that does not have a concrete floor. If crops are being grown directly in the soil, an ETS system will not only conserve energy but will function as a root zone heating system. As a result, plant development may accelerate and crop yield may increase (Figs. 3 and 4).

Fig. 3. *Five-week-old cauliflower, cabbage, and broccoli crops in an ETS solar quonset house. Note that rows almost touch one another.*

Fig. 4. *Five-week-old cauliflower, cabbage, and broccoli crops in an unheated quonset house. Note slower plant development.*

Fig. 5. *A porous concrete floor for water drainage.*

After the ETS system is installed, the floor can be covered with gravel, wood chips, or porous concrete. Porous concrete (Fig. 5) is a mixture of cement and gravel without the addition of sand. Water flows readily through the void spaces around the stones. It is important to allow excess irrigation water to flow into the soil around the pipes to prevent the soil from drying out. If the soil is allowed to dehydrate, its thermal conductivity and heat storage capacity decreases substantially (National Research Council of Canada 1977). Furthermore, the soil may shrink, causing it to separate its contact with the pipes. This would drastically reduce heat transfer rates between the pipes and the soil. Soil shrinkage could also crack and damage the concrete floor.

For second-stage cooling in glass gable greenhouses, natural ventilation is preferable to forced ventilation, because exhaust fans are costly to operate. In greenhouse sections with sidewall and ridge ventilators (Fig. 6), the sidewall ventilator should be opened first to prevent the escape of accumulated excess heat in the peak. This warm air is then drawn into the buried pipes, allowing cooler air to rise and take its place. The ridge ventilators should only be opened when the inside air temperature increases well above the set point or if the thermal storage is fully charged.

Fig. 6. *An even-span gable greenhouse with the sidewall ventilator opened first, followed by the leeward ridge ventilator.*

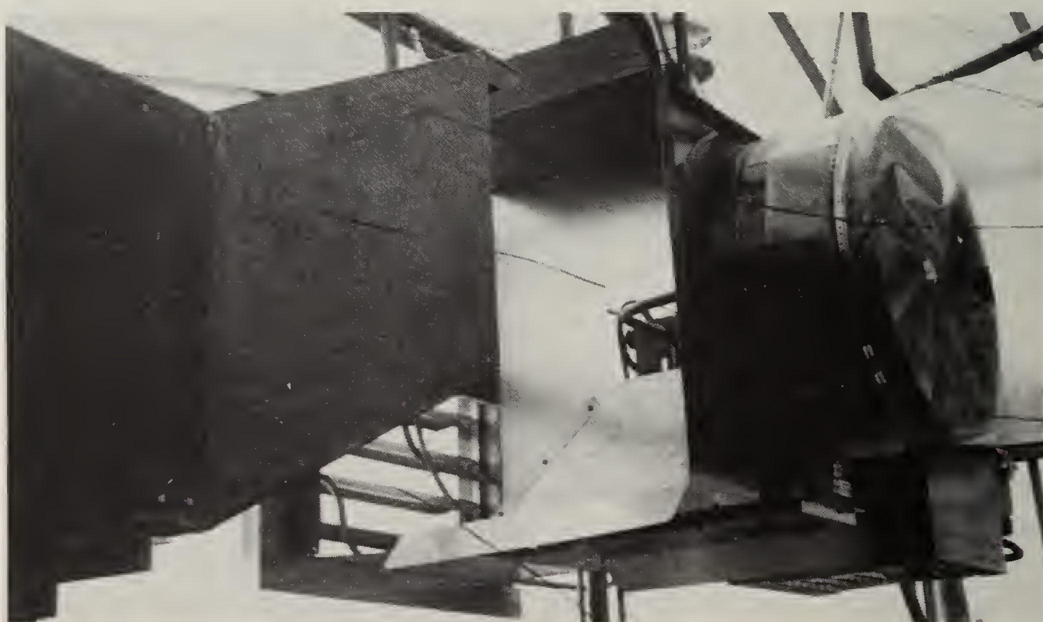


Fig. 7. *A fan jet and perforated convection tube system with heat kit. The duct conveying warm air from the solar storage is on the left. The propane unit heater is at the right.*

In polyethylene houses, forced ventilation is often used in the absence of either sidewall or ridge ventilators. Fans with perforated polyethylene convection tubes are popular (Fig. 7). Sometimes a heat kit is installed behind the fan. This allows warm air that is being blown out of the thermal storage and/or unit heater to be distributed down the perforated tube. If the perforations in the tube are pointed upward, the hot air blows across the greenhouse roof rather than directly onto the crop. Some plants, including tomatoes, do not transpire properly if hot air is blown onto their leaves. Also, air movement against the roof diminishes water condensation drops.

Fig. 8. *A polyethylene sidewall ventilator rolled up on shaft.*

Fig. 9. *An inflated polyethylene sidewall ventilator closed with a tight seal.*

Reduced condensation decreases condensation heat losses and the threat of disease spreading. It also increases light transmittance through the cover during the day.

Double-polyethylene greenhouses can be cooled with natural ventilation by installing roll-up sidewall ventilators (Figs. 8 and 9). If the ventilators are inflated with a small centrifugal fan, they will form a tight seal when closed and reduce heat loss across the plastic layers. The shaft that winds the ventilator up and down can be motorized. This eliminates manual labor and provides automatic control, but the cost is prohibitive relative to the cost of the structure.

Design guidelines

The design guidelines that follow are based upon experimental results from the work at Saanichton and recommendations included in other research publications. To assist readers, examples are given of how some of the guidelines would apply in a greenhouse about 930 m² in size. It is assumed that the greenhouse has a length of 48 m and a width of 19.2 m. The dimensions are based on the column spacings of a Venlo-style gable glasshouse.

Pipe material selection

ETS studies in Japan concluded that the total surface area of the buried pipes should at least equal the surface area of the greenhouse floor (Sasaki and Itagi 1979). The surface area of the pipes is determined by their diameter and spacing. These factors also influence the amount of air that can be conveyed by the pipes. After taking all parameters into consideration, the Japanese researchers concluded that a pipe diameter of 10 cm is ideal.

The ETS pipes are not subjected to much pressure either from the air or from the surrounding soil. Since the pipe walls do not have to be very strong, inexpensive drainage pipe or sewer pipe is adequate. The cheapest material available is non-perforated, corrugated, drainage tubing. However, the corrugations greatly increase the friction between the moving air and the pipe wall. In their comprehensive design guide for underground heat storage, Lawand et al. (1985) report that corrugated pipe has 3.2 times the pressure loss of smooth 10 cm ID (internal diameter) pipe. This means that about three times as much fan power is required to move an equivalent amount of air through corrugated pipe.

One might think that corrugated pipes are capable of transferring more heat to the surrounding soil than smooth pipes because of their greater surface area. However, Sibley and Raghavan (1984) measured the heat transfer coefficients of a variety of corrugated drainage tubes and found that their heat transfer coefficients were similar in magnitude but somewhat less than those found in smooth pipes. Calculations show that corrugated and smooth pipes transfer similar amounts of heat overall for a given airflow.

One of the cheapest smooth pipe materials available is ASTM 2729 plastic drain pipe; it costs about $1.15 (1986 funds) per metre more than corrugated drainage tubing. A 930-m² greenhouse requires about 3170 m of ETS pipe, allowing for some extra waste material. If corrugated tubing is selected, the capital cost saving is approximately $3650.

The additional electricity required for the fans to overcome the increased friction costs about $245 annually. As a result, the smooth pipes should pay for themselves over a 15-year period and will provide operating cost savings over the remaining 15 years of the system's life. However, the difficulty of transporting rigid pipes and the additional labor required to install them in the ground must also be taken into account. Once these factors have been considered, it would seem that 10 cm ID non-perforated, corrugated, drainage tubing is the superior material for the ETS system. Since common perforated tubing fills with water, preventing airflow, non-perforated tubing should be used for the ETS application.

Pipe length, spacing, depth, and slope

Lawand et al. (1985) recommend pipe lengths between 10 m and 20 m for maximum efficiencies in ETS applications. Accordingly, in greenhouses more than 20 m long, the configuration of the fan, plenums, and pipes should be similar to the one depicted in Fig. 10. If the greenhouse is longer than 40 m, two sets of ETS systems should be installed end-to-end.

The fans can either draw air from the pipes (negative pressure, Fig. 10) or blow air into the pipes (positive pressure, Fig. 1). In the first instance, air enters intake ducts above the end plenums and is exhausted through outlets above the fan mounted on the central plenum (Fig. 10). Alternatively, air enters an intake above the fan on the central plenum and is exhausted through outlets above the end plenums (not illustrated).

The location of the fan on the central plenum is not critical, nor is the location of the inlet or outlet ducts. Shading can be reduced by locating ductwork in the corners of the house or at the sidewalls. However, an even air distribution is important for maximum efficiency; therefore, the number of ducts and their location should be selected to balance the air distribution. In Venlo-style greenhouses, the air intake height need only be as high as the gutters. In all ETS systems, the exhaust air should be blown across the top of the crop. Perforated convection tubes are ideal for distribution of the exhaust air.

In our example of the 48-m-long greenhouse we can assume that the plenum chambers would occupy approximately 2 m of the overall length. Since the pipe length should not exceed 20 m, it would be necessary to install two ETS systems end-to-end. This would result in individual pipe lengths of 11.5 m, which falls within the specified design criterion.

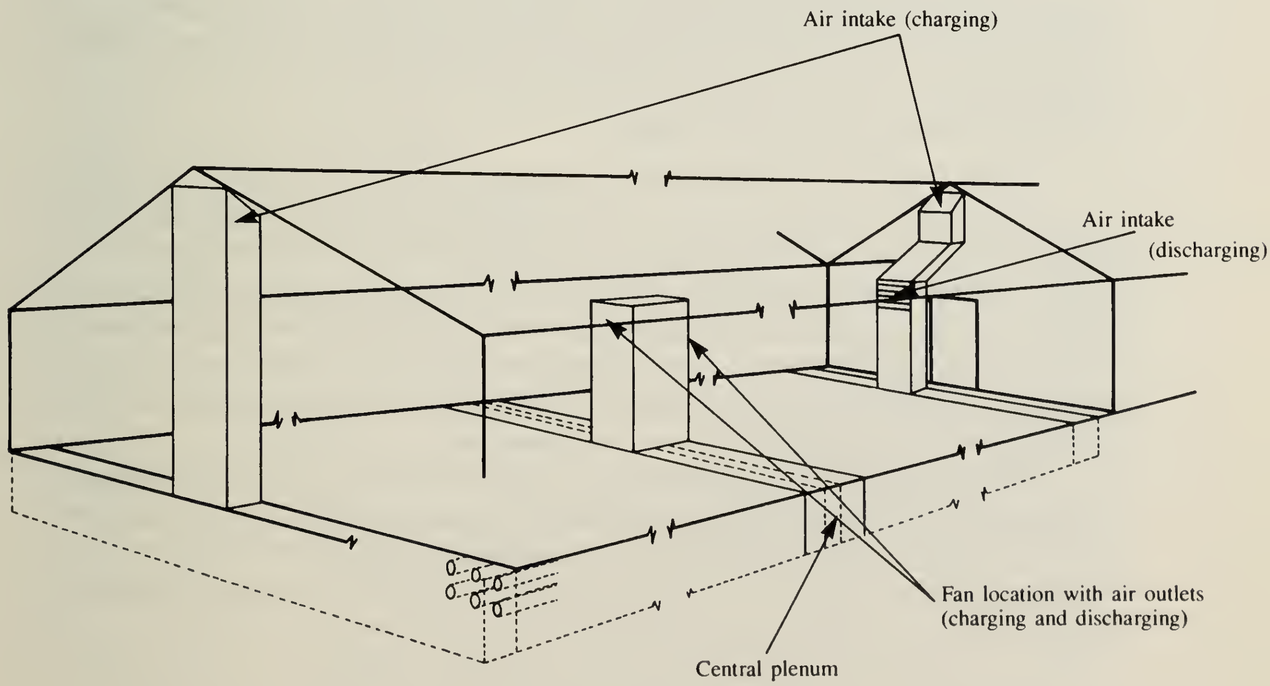


Fig. 10. *An ETS heating system for conventional greenhouses more than 20 m long.*

Lawand et al. (1985) determined that the minimum pipe spacing should be at least 40 to 60 cm centre-to-centre. Based on the ETS performance at Saanichton, the authors recommend a lateral pipe spacing of 55 cm. This takes into account the pipe surface area requirement, as stipulated by Sasaki and Itagi (1979). It also provides for an adequate number of pipes to convey the required airflow rate, while maintaining an acceptable cost for the pipe material.

Although our example greenhouse is 19.2 m wide, a clearance space must be left between columns and adjacent pipes of about 30 cm centre-to-centre. This allows clearance for the concrete friction footings that support the columns. Let us assume that besides the exterior columns, there are two rows of internal truss support columns. This will reduce the effective ETS field width by 1.8 m, leaving 17.4 m of available space.

A 55-cm lateral pipe spacing will allow 33 rows of pipes to be installed if the outside rows are squeezed in slightly. The total number of pipes in this ETS system will equal 33 rows × 2 layers × 4 pipe lengths, resulting in a total of 264 pipes.

The pipes should be installed at depths of 40 and 80 cm, floor grade to centres. These depths meet the minimum spacing requirements and result in an effective and adequate storage depth of about 1 m. At the same time, trenching and installation costs are minimized.

When the greenhouse air is hot and very humid and the storage temperature is sufficiently lower, water may condense out of the air into the ETS pipes. To facilitate drainage of the condensate, the pipes should be installed at a 0.5% slope downward in the direction of airflow. The condensate then flows into the soil at the bottom of the plenum chamber where it drains away to the perimeter drainage system.

If only one plenum chamber is installed, as shown in Fig. 2, the direction of the airflow and the pipe slope must be toward the plenum; otherwise, the condensate will not drain from the pipes, preventing dehumidification from occurring.

Air circulation rate and fan sizing

As the total air circulation rate increases, the heat transfer rate in the pipes increases, as does the amount of energy available for storage. It follows that the capacity and responsiveness of the ETS system will improve as a result. However, the power required to move air increases exponentially by a power of three as the airflow rates increase. With increased airflow rates, a point is reached where the overall system efficiency starts to decline. If excessive input energy is required to operate the solar system, the net energy savings become too low for economic returns.

The optimum air velocity in the pipes is about 2 m/s, according to Lawand et al. (1985). Despite this, they report that velocities of 5 m/s, or more, are acceptable in ETS systems with short pipe lengths (5 to 10 m) or fewer fittings, such as elbows or transition sections, which cause large dynamic losses. A velocity of 2 m/s corresponds to an airflow rate of 0.016 m^3/s per pipe at a pressure loss of 35 Pa, given a length of 15 m.

Research at Saanichton indicates that the ETS system performance is most efficient when the air circulation rate moves the total volume of air in the greenhouse through the pipes once every 9 min.

If the Venlo-type greenhouse in our study has a gutter height of 3 m, then the volume is approximately 3130 m^3. The total airflow rate should therefore be 5.80 m^3/s, which is equivalent to 0.022 m^3/s in each of the 264 pipes. The pipe air velocity is 2.7 m/s. This may initially appear to be excessively high but the pipe lengths are near the lower end of the recommended range. A calculation of the pressure drop will determine if the design is adequate. Using methods outlined in the ASHRAE handbook, *Fundamentals* (American Society of Heating, Refrigerating and Air-Conditioning 1981), and data taken from Carson et al. (1980), a pressure loss of 50 Pa is calculated. Depending on the design of the inlets, outlets, and transitions from the pipes to the plenums, as well as the number of elbows, the total pressure loss may be anywhere from 100 to 150 Pa.

Our design example requires two fans, each capable of moving 2.9 m^3/s against the total pressure loss. These fans require a motor size of about 1.87 kW. The studies at Saanichton have shown that a 930-m^2 greenhouse requiring 3.7 kW of solar fan input energy is economical to operate (see Annual operating costs and returns, p. 22). For an actual ETS system design, the system pressure losses would have to be carefully determined according to the methods recommended by ASHRAE.

Plenums and ductwork

The plenum chambers can be built with pressure-treated plywood and 2″ × 4″s (5 × 10 cm), and these should extend across the full width of the greenhouse. The covers should be sealed well to eliminate air leakage. It is not advisable to cover the bottom of the plenum, otherwise condensate from the pipes cannot drain away.

The ductwork is usually constructed of plywood and 10-cm cant strip, and should be painted white to reflect light onto the crop.

An ETS system requires a smooth, aerodynamically efficient network of plenums and ducts. The details of the configuration, the intersections of the components, and their dimensions should be checked by an expert. The operation of an ETS system cannot be economical if the airflow pressure losses are unacceptably high.

Below-grade perimeter insulation

Since stored heat does not migrate very far below the lower pipes, there is no need to install insulation below the storage. However, heat moves laterally from the storage to colder external soil. Heat loss to the outside ground can be controlled by installing perimeter insulation to a depth of 1.2 m. This will also provide frost protection for the column footings. The material should have an insulation value of at least R_{SI} = 0.9 $m^2{}^\circ C/W$ (R = 5 $ft^2h{}^\circ F/BTU$) but it can be cost effective up to R_{SI} = 2.6 $m^2{}^\circ C/W$ (R = 15 $ft^2h{}^\circ F/BTU$) (Towning and Turkewitsch 1981). The cost of excavation is included if the insulation is installed in either the perimeter drain trench or the outside pipe trenches.

Installation costs

The total capital costs to install an ETS system similar to that depicted in Fig. 10 in a 930-m^2, even-span gable house are about $11.40/$m^2$ (1985 funds).

Labor costs to install the pipes, fans, and electrical connections are also included. It is assumed that growers will supply their own labor to build the ducts.

Annual operating costs and returns

The experimental ETS system at Saanichton has reduced the heating requirements of a commercially sized gable glasshouse by 25.1% annually, compared to an identical control structure. However, electrical energy consumption has been 33.6% higher due to the power requirements of the solar fan. This translates to a total energy savings of 22.1%, given that the ratio of heat energy to electrical energy requirements in the control house is 19.25:1.

Agriculture Canada made all the experimental data concerning capital and operating costs available to Arcus Consulting Limited, independent specialists in agricultural economics. They summarized the annual costs and returns, using estimates of annual maintenance costs as supplied by the researchers at Saanichton. The cost of propane was assumed to be $0.2275/L, and the overall efficiency of the conventional hot water boiler heating system was calculated at 75%. The electricity costs selected were $0.0619/kWh for the first 550 kWh consumed per month and $0.0431/kWh for any additional monthly consumption.

Economic analysis

Arcus Consulting Limited (1985) determined the net present value and benefit–cost ratios for the ETS system. The benefit–cost ratios were 1.8, 1.4, and 1.1 for interest rates of 5, 10, and 15%. The internal rate of return was estimated to be 18% per annum.

The results showed that the ETS system has potential economic viability at all three rates of interest, assuming that the performance measured is the same as that measured at Saanichton. The technology will likely be most profitable at low interest rates.

The analysis was repeated, assuming that No. 2 fuel oil was the fossil fuel being used at a cost of $0.2690/L. In this analysis, the overall efficiency of the conventional heating system was calculated at 65%. With oil, the benefit–cost ratios are 3.5, 2.7, and 2.2 for each of the three rates of interest, respectively. The internal rate of return is then 55% per annum.

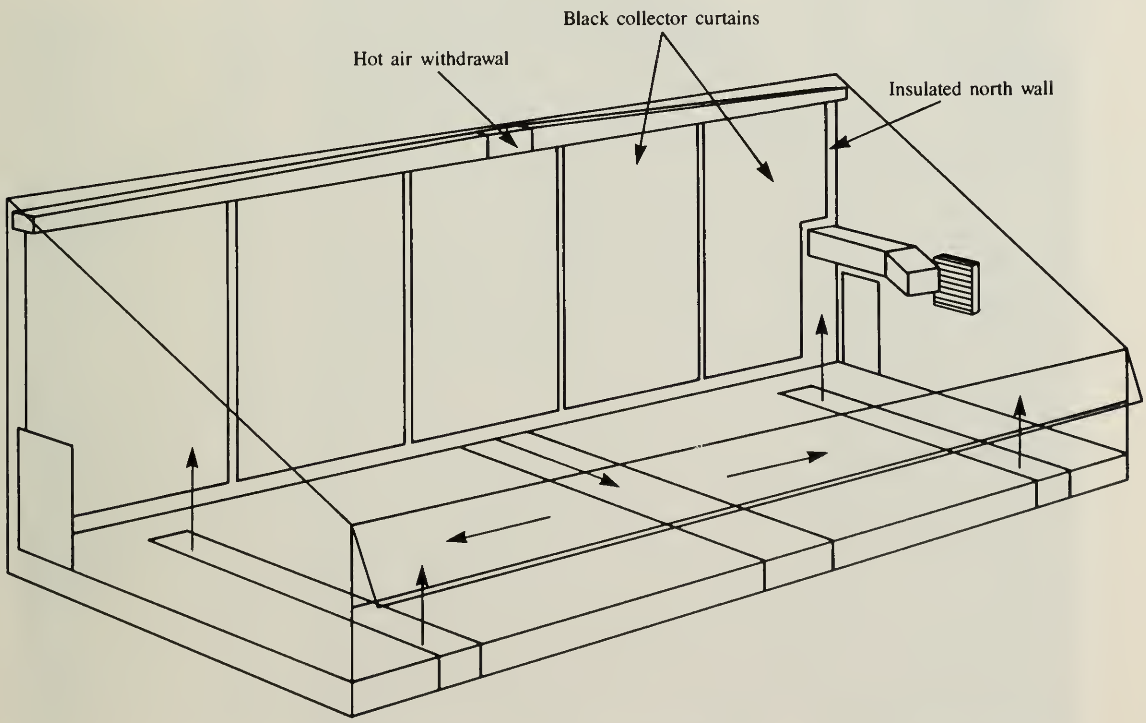
Arcus Consulting Limited also studied the economics of installing an ETS heating system in an unheated double-polyethylene quonset with vegetable crops grown directly in the soil. It was concluded that the system is not economic under any conditions if the benefits are based on increased vegetable production due to the effect of elevated night temperatures, an extended growing season, and root zone heating. An economic analysis of ETS systems in heated double-polyethylene quonsets based on energy savings alone is not available.

Shed-Type Solar Heating System

Description

The shed-type solar greenhouse (Fig. 11) is designed for northern latitudes above 52°, where the sun is closer to the horizon and winters are extremely cold. The east-west-oriented structure is formed from one half of a conventional galvanized steel and aluminum gable frame with an insulated vertical north wall. Since the resulting configuration is costly to build, has a narrow width, and shades the area to the north, its application is limited. It can only be installed during the initial construction of a greenhouse. Therefore, it is not described here in as much detail as the ETS system.

The shed-type profile has a greater ratio of glazed surface area to floor area than a conventional gable structure. Consequently, it transmits 30–45% more light to the interior on a unit floor area basis, depending upon the month (Lau et al. 1984). An insulated north wall will reduce heat loads by 15% compared to an uninsulated gable glasshouse of equal area.



Arrows indicate airflow during charging procedure.

Fig. 11. *A heating system design for detached shed-type greenhouses.*

Solar-collecting panels made of reinforced polyethylene covered in flat black latex paint to increase absorptivity hang in front of the insulated wall. They are suspended from a scroll attached to a hot-air collecting duct in the peak and are designed to be rolled up and down, according to the demand for heat and the height of the crop. The inside surface of the north wall insulation is painted with white high-gloss interior latex paint. This paint protects polystyrene insulation, whereas other paints may corrode the insulation material. When the collecting panels are rolled up, the white surface is designed to reflect light onto the crop and also to reflect excess radiation out of the greenhouse (Fig. 12). The reflective paint also increases the efficiency of the solar-collecting panels when they are rolled down, because light passing around the panels is reflected back onto the inside collector surface.

Fig. 12. *An insulated north wall in a shed-type greenhouse. The solar-collecting panels, which are suspended from a scroll, are retracted to reflect light.*

The vertical slope of the collecting panels results in maximum efficiencies in spring and fall because the sun's rays strike the collecting panels at a lower angle. The panels heat the air surrounding both sides, causing the air to rise passively toward the peak.

A large electric centrifugal fan draws the heated air into the duct and transfers it to rock storages beneath the greenhouse floor (Fig. 13). The air is then forced through void spaces between the rocks, which absorb the heat. The cooled and dehumidified air is subsequently returned to the greenhouse interior. If the temperature of the air exiting the storages reaches the inlet air temperature, the storages are fully charged. The solar fan should not be operated in the charging position again until some heat has been recovered from the storages.

The stored heat should be released at night by reversing the airflow direction, using motorized dampers in the ductwork surrounding the fan (Fig. 14). Rock storages develop longitudinal temperature stratifications during charging. In contrast to earth thermal storages, the regions near the point where the hot air enters become warmer than the opposite ends. Airflow reversal during discharge allows the circulated air to pass through the warmest rocks before reentering the greenhouse. This ensures that the recovered heat is available at the maximum possible temperature. If the discharged air temperature falls below the interior temperature, the solar fan should be shut off until more heat is collected.

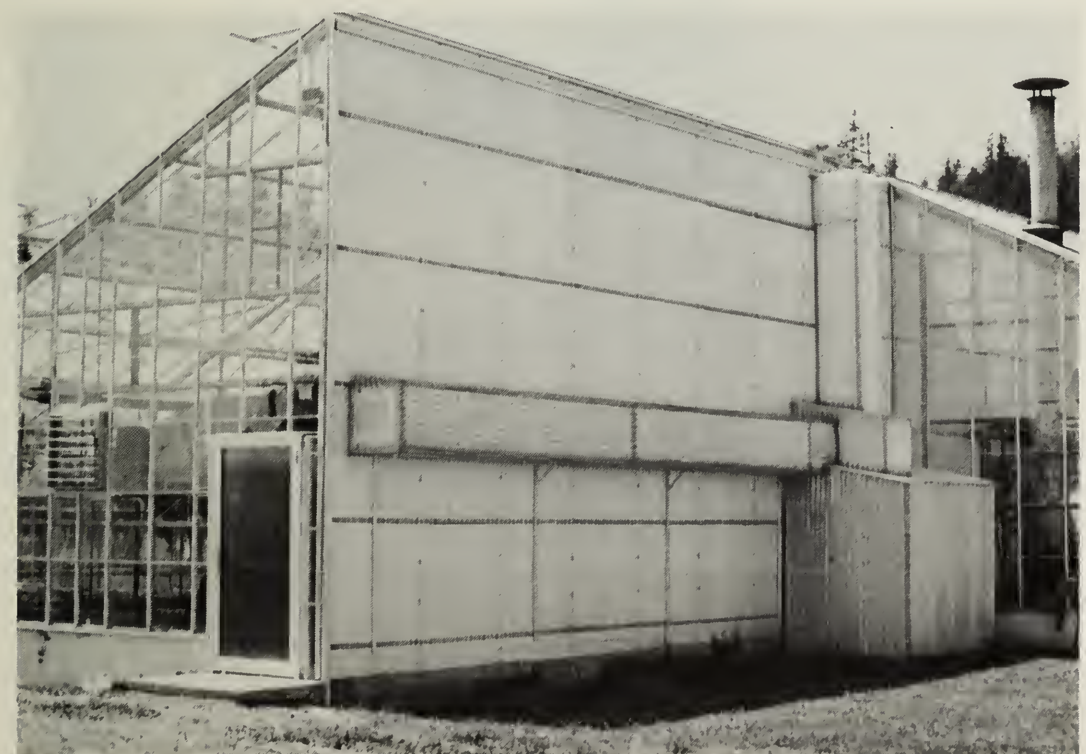


Fig. 13. *An insulated north wall and solar fan.*

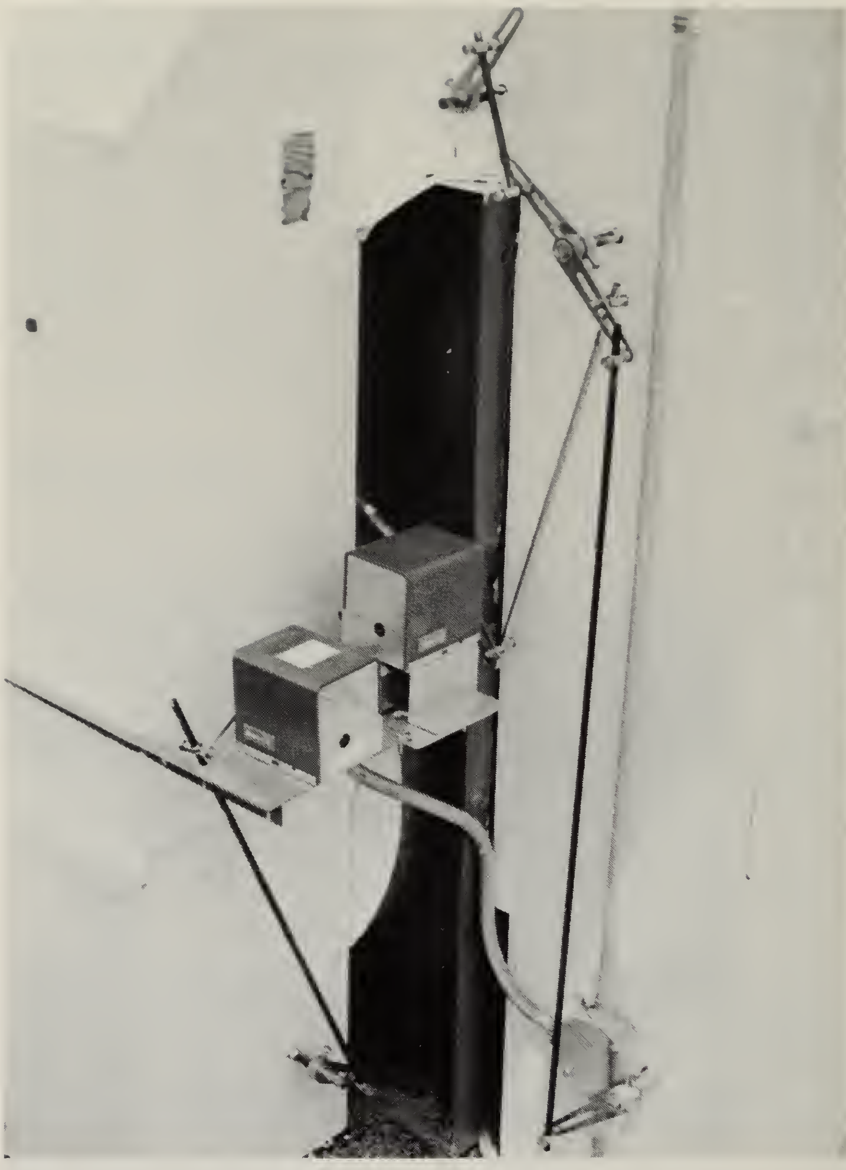


Fig. 14. *Motorized dampers for airflow reversal.*

Applications

The shed-type solar heating system is only compatible with an east–west alignment. The covering material must not diffuse the transmitted light, because the collecting panels only function effectively with direct-beam radiation. The only practical glazing is therefore single-layer glass.

Experiments at Saanichton have shown that the shed's collecting panels are capable of collecting far more heat than can be contained in rock storages beneath the shed's floor. On a commercial scale the system is only economically feasible if it is gutter-connected to a second east–west-oriented, even-span gable glasshouse to the south containing additional rock storages beneath its floor (Fig. 15). By adding the gutter-connected structure, the cost of the insulated north wall, collector, and solar fan will apply to three times as much greenhouse floor area.

Air pressures in rock storages must be fairly high in order to force circulation through the void spaces. To ensure a tight seal, the rock storages should be covered with polyethylene before the floor material is placed on top. The polyethylene also prevents excess irrigation water from entering the rock storages. A 10-cm layer of fine gravel or coarse sand is sufficient to hold the polyethylene in place. Alternatively, a solid concrete floor can be laid down.

Natural ventilation by means of a ridge ventilator does not work in a solar-heated shed. For one thing, a ridge ventilator cannot provide sufficient cooling capacity because some outside air is drawn into the peak collecting duct. Also, the resulting downdrafts interfere with the passive movement of hot air that rises from the collector. The best method of ventilation is to install a fan jet convection system above the crop, with shutters at each end to allow outside air to flow across the greenhouse. The warm air recovered from the rock storages can be ducted into a heat kit whenever solar heating is required. Another method is to install exhaust fans with shutters. Although exhaust fans with shutters do not distribute the solar heat, they are desirable if evaporative cooling pads are required to maintain acceptable maximum daytime temperatures. In addition, a solar fan will have adequate power to distribute the discharged solar-heated air down a perforated convection tube if the air-handling system has been properly designed, thereby eliminating the requirement for a fan jet.

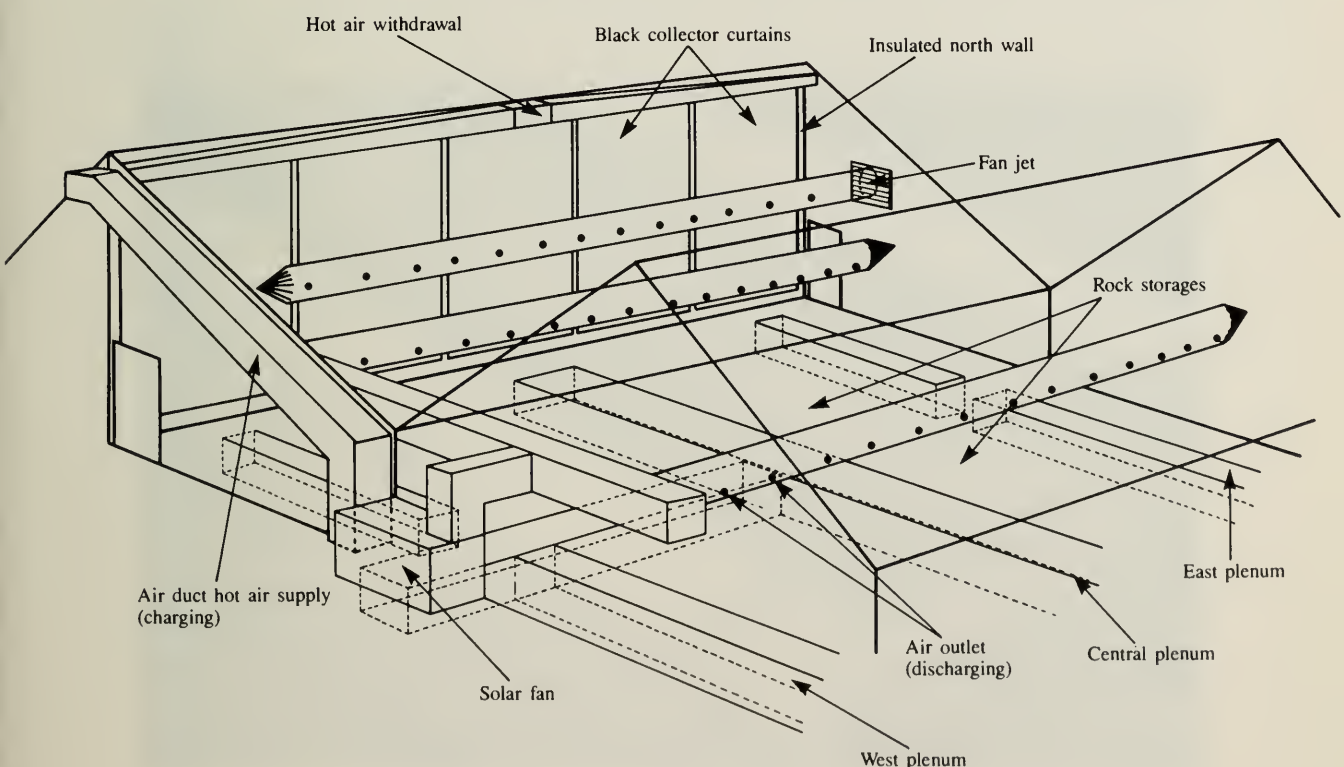


Fig. 15. *A heating system design for gutter-connected, shed-type greenhouses.*

Design guidelines

The airflow dynamics in rock storages are very complex and depend upon numerous critical factors, including the air circulation rate, the individual rock size range, the void space ratio, and the dimensions of the storages. Consequently, it is impossible to offer design guidelines such as those discussed for the ETS system. Readers who wish to gain an understanding of the airflow principles involved are referred to publications by the National Research Council of Canada (1979, 1980, and 1981*a*).

The air circulation rate is determined by the characteristics of the solar radiation available at the site and the dimensions of the shed and its collector. A monthly analysis of the anticipated solar collector performance should be performed according to the principles outlined by the National Research Council of Canada (1977). The duct design and fan sizing are determined, using the guidelines published in ASHRAE handbook, *Fundamentals* (American Society of Heating, Refrigerating and Air-Conditioning 1981).

The ductwork can be built with the same materials that are used for the ETS system (plywood and 10-cm cant strip), and should also be painted white to reflect sunlight. The plenum chambers in the experimental house at Saanichton are made with concrete block. Because the outer walls of the plenum chambers at the ends of the storages must be airtight, the blocks are laid on end in conventional fashion. The walls of the central plenum and the inside walls of the plenums at the ends of the storages must contain large holes to allow air to pass through and be strong enough to resist the lateral load imposed by the rock beds. To facilitate these requirements, the blocks are laid sideways and their inner surfaces are covered with two layers of 13-mm steel mesh to prevent rock from falling through (Fig. 16).

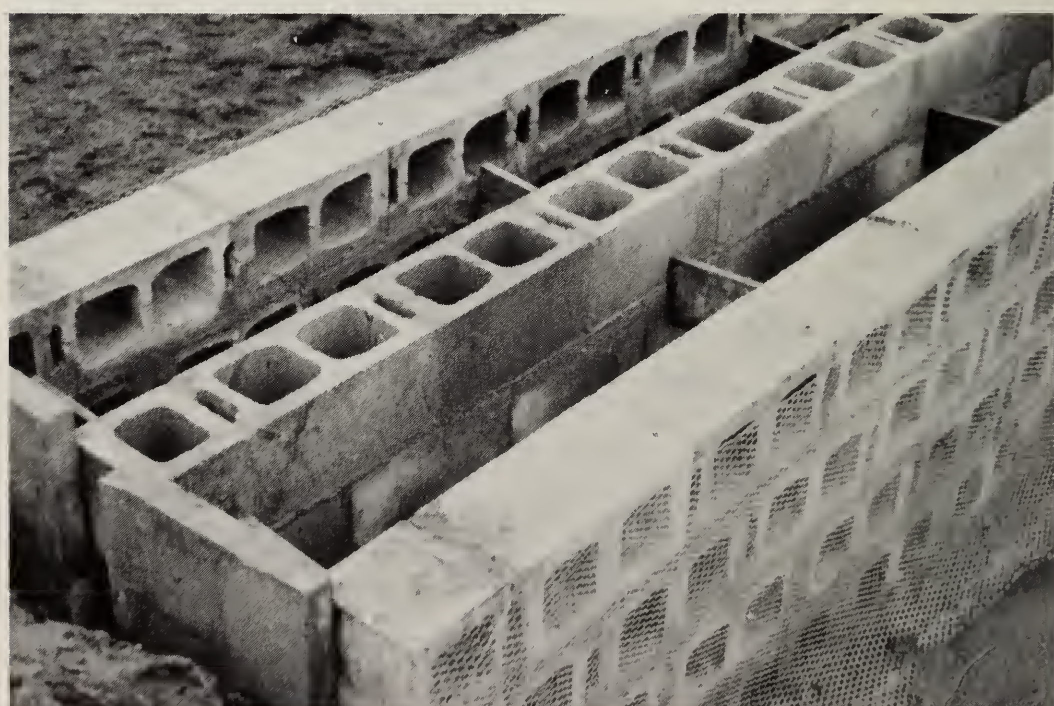


Fig. 16. *A concrete block plenum construction.*

The top, bottom, and sides of the rock storages and the north wall should be insulated with a material that has an insulation value of at least R_{si} = 0.9 m²°C/W (R = 5 ft²h°F/BTU). Extruded polystyrene foam is ideal for this purpose. The rock storage should also be sealed with a vapor barrier of 0.15-mm (6-mil) polyethylene film. The outside surface of the north wall can be covered with an inexpensive material that is easy to install, such as fiberglass.

Installation costs

Typical installation costs for a 945-m² solar shed gutter connected to an even-span gable glasshouse are about $35.00/m² (1985 funds). The solar shed is assumed to be one half of a standard 12.8 m × 54.9 m gable house. Dimensions of the gutter-connected house are 10.8 × 54.9 m.

Annual operating costs and returns

During tests done at Saanichton, a solar shed used 47% less heat energy and 73.1% more electricity than a gable house, for an overall energy savings of 40.3%.

Agriculture Canada supplied Arcus Consulting Limited with cost and energy saving data for the experiments. The company determined the annual costs, using similar methodology to that which was applied to the ETS system.

Economic analysis

The benefit–cost ratios for the 945-m² solar shed gutter-connected unit with natural gas heating are 1.3, 1.0, and 0.7 at interest rates of 5, 10, and 15%, respectively. The internal rate of return for this technology is 9% per annum. The results show that with this fossil fuel the solar shed system may only be economically feasible at an interest rate of 5%.

The technology has a higher net present value, a higher benefit–cost ratio, and an internal rate of return when No. 2 fuel oil is used for heating. With this method of heating, the system was economic at all three rates of interest studied. Benefit–cost ratios observed were 2.5, 1.8, and 1.4, respectively, and the internal rate of return increased to 25% per annum.

Despite the fact that the solar shed is capable of delivering significantly higher energy savings than the ETS system, its higher capital costs result in much lower economic potential. For many reasons, the ETS system is better suited for commercial application.

Water Storage Heating Systems

The heat storage capacity of water is 2.8 times greater than that of rock and is similar to that of wet soil. However, solar systems that use water as a heat-transfer fluid are costly, restricting their use in commercial greenhouse applications. The large collectors must be situated outside the greenhouse, which presents problems in gutter-connected ranges. These systems are also often plagued with leaky fittings.

In several research projects external solar collectors were used with hot water storage in insulated tanks. It was found that the collector area to greenhouse floor area ratio must be 1:1 to provide significant energy savings. The high capital investment required to install such a system and the high cost of the land occupied by the solar collectors are not offset by the savings achieved. The resulting pay back period is 15–20 years.

Solar ponds are open bodies of water that simultaneously collect and store solar energy by absorbing the sun's rays. They can be installed inside a greenhouse, but the floor area they occupy cannot be used to grow crops. The hindrances that internal solar ponds create also make plant transportation difficult.

Barrels or other containers can be filled with water and stacked against an insulated north wall, where they are exposed to the sun's radiation (Fig. 17). They absorb heat during the daytime. At night the accumulated heat is passively radiated back into the greenhouse interior. Although this simple application of solar heating only provides a significant energy savings in small greenhouses, the low cost can make this technique cost effective.

Fig. 17. *Water barrels that are used as heat storage in a small greenhouse.*

Environmental Control for Solar Greenhouses

To ensure optimum efficiency of solar heating systems, the environmental control equipment must be responsive to changing heat balances inside the greenhouse. Set point temperatures must be maintained, regardless of the heating method used for the greenhouse.

Greenhouses that are heated by a combination of two different heating systems require advanced environmental control devices in order to function effectively. Solar systems operate most efficiently when ventilation and cooling equipment and the first and second stages of heating are initiated at the correct temperature. The sequence of these functions must be defined properly. To better understand possible sequences, various steps are described for a typical ETS greenhouse. The temperature set points are assumed to be 18°C during daytime and 21°C at nighttime.

The first stage of cooling is initiated when the interior air temperature rises above the set point. At approximately 23°C the solar fan starts operating, resulting in the withdrawal of hot air into the pipe network. Interior temperatures stabilize when climatic conditions permit.

The second stage of cooling is initiated when increased solar radiation causes the interior air temperature to rise farther. At approximatley 25°C the side ventilator opens, then the ridge ventilator opens. In the case of gutter connection, the exhaust fans are switched on sequentially. More advanced controls stop the charging if the inlet air temperature falls below the soil temperature. This situation sometimes occurs after several days of bright sunshine, during which the storages reach maximum temperature. Operation of the solar fan for heating must be locked out if the storages are empty until more heat is collected.

The solar fan does not operate at the set point temperatures, and will only withdraw heat from the storages if the interior air temperature drops below the set point by more than 1.5°C. If the temperature falls another 1.5°, the conventional heating system turns on.

Conclusions

In certain areas of Canada where climatic factors are favorable, an earth thermal storage solar greenhouse may be economically feasible, based on experimental results obtained at the Agriculture Canada research station in Saanichton, B.C. The technology is suitable for any new greenhouse regardless of structure, covering, or orientation. It can easily be retrofitted into existing greenhouses provided they do not have concrete floors. A grower who is considering using this technology is advised to carefully consider the topics discussed in this brochure before proceeding. An agricultural engineer should approve a solar-heating design, because it is critical for efficient operation.

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Appendixes

Appendix A

The following weather stations correspond to the numbers in Tables 1–5:

No.	Station	Province
1	Agassiz	British Columbia
2	Kamloops	British Columbia
3	Kimberley	British Columbia
4	Prince George	British Columbia
5	Summerland	British Columbia
6	Vancouver	British Columbia
7	Victoria	British Columbia
8	Brooks	Alberta
9	Calgary	Alberta
10	Edmonton	Alberta
11	Grand Prairie	Alberta
12	Lethbridge	Alberta
13	Medicine Hat	Alberta
14	Estevan	Saskatchewan
15	Moose Jaw	Saskatchewan
16	Regina	Saskatchewan
17	Rosetown	Saskatchewan
18	Saskatoon	Saskatchewan
19	Swift Current	Saskatchewan
20	Yorkton	Saskatchewan
21	Cypress River	Manitoba
22	Morden	Manitoba
23	Portage La Prairie	Manitoba
24	Rivers	Manitoba
25	Winnipeg	Manitoba
26	Brockville	Ontario
27	London	Ontario
28	North Bay	Ontario
29	Ottawa	Ontario
30	Peterborough	Ontario
31	Sudbury	Ontario
32	Toronto	Ontario
33	Windsor	Ontario
34	Drummondville	Quebec
35	Montreal	Quebec
36	Quebec	Quebec
37	Sherbrooke	Quebec
38	Tadoussac	Quebec
39	Trois Rivières	Quebec
40	Gander	Newfoundland
41	St. John's	Newfoundland
42	Stephenville	Newfoundland
43	Fredericton	New Brunswick
44	Moncton	New Brunswick
45	Saint John	New Brunswick
46	Charlottetown	Prince Edward Island
47	Halifax	Nova Scotia
48	Sydney	Nova Scotia

Table 1. Mean values of daily global solar radiation (MJ/m^2) on a horizontal surface

Weather Stn	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
4	2.73	5.30	10.09	15.79	18.15	21.42	20.81	17.04	11.12	6.14	3.07	1.78
5	3.44	6.48	11.54	16.66	20.82	22.64	23.68	19.55	14.47	8.45	3.82	2.50
6	2.94	5.53	10.03	15.09	20.15	21.78	22.95	18.62	13.22	7.38	3.59	2.28
10	3.65	7.09	12.43	17.53	20.21	21.87	21.89	18.09	12.11	7.69	3.95	2.59
19	5.05	8.72	14.05	17.86	21.58	23.14	24.35	20.13	14.36	9.45	5.27	3.83
25	5.25	9.05	14.06	17.74	20.90	22.74	22.99	19.00	13.32	8.15	4.64	3.82
29	5.74	9.44	13.61	16.75	19.88	21.37	21.28	18.11	13.36	8.58	4.72	4.33
32	6.09	9.33	12.92	17.33	19.96	21.74	21.94	18.74	14.09	9.14	4.79	4.33
35	5.30	8.80	12.51	15.87	19.07	20.25	20.96	17.23	13.45	8.04	4.61	3.92
41	4.14	7.08	10.42	13.60	16.54	19.60	19.94	15.72	12.02	6.82	4.11	3.03
43	5.48	8.92	12.35	15.32	17.94	19.91	19.61	17.32	13.20	8.50	5.05	4.12
46	5.32	8.97	12.61	15.88	18.57	20.92	20.10	17.71	12.93	7.90	4.94	3.79
47	5.11	8.14	12.09	14.54	17.38	20.00	19.11	17.94	13.98	8.96	5.32	3.85

Table 2. Average monthly and total annual duration of bright sunshine in hours

Weather Stn	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Annual
1	42	68	102	135	177	174	246	210	157	105	58	35	1818
2	54	93	150	187	245	244	208	275	194	121	63	43	1977
3	31	109	183	181	276	242	346	307	182	146	89	32	2124
4	54	89	139	187	255	256	279	245	158	104	60	39	1865
5	49	83	148	198	250	261	320	277	206	140	63	40	2040
6	55	93	129	180	253	243	305	255	188	116	70	44	1931
7	70	98	150	198	277	176	338	287	209	139	81	60	2183
8	88	116	158	206	270	287	341	304	201	173	111	76	2334
9	99	121	156	196	237	240	317	278	188	166	116	94	2208
10	91	113	176	223	272	265	306	269	185	161	105	80	2237
11	83	116	154	204	245	254	281	246	163	151	93	66	2056
12	95	123	167	198	263	284	345	299	213	175	116	90	2370
13	91	118	149	199	256	261	342	292	188	165	105	86	2170
14	121	135	185	210	289	303	356	310	212	188	120	103	2536
15	105	125	166	218	279	285	344	297	202	173	110	85	2394
16	98	117	156	210	271	253	337	293	194	169	96	83	2277
17	99	117	163	208	279	283	334	290	179	157	95	77	2281
18	99	129	192	225	279	280	342	294	207	175	98	84	2403
19	92	114	156	208	177	281	342	297	194	168	110	85	2328
20	108	129	165	223	281	288	329	285	184	157	90	87	2328
21	115	136	158	202	253	260	313	272	186	158	96	94	2241
22	115	136	158	201	252	260	312	272	185	157	96	93	2241
23	121	144	176	220	266	276	316	283	185	152	91	93	2321
24	116	141	174	210	261	270	339	294	193	170	93	94	2359
25	112	139	170	209	246	259	331	276	183	158	81	86	2230
26	104	115	171	206	258	264	302	264	189	152	81	81	2186
27	69	96	128	170	233	243	274	253	177	153	73	61	1930
28	97	130	158	188	231	246	267	226	158	115	59	70	1945
29	96	115	150	175	231	245	277	243	171	138	76	78	1995
30	73	101	133	165	228	236	270	224	168	132	73	40	1843
31	100	131	152	207	247	246	288	251	150	122	77	84	2060
32	87	110	145	179	221	256	281	256	197	153	82	77	2045
33	83	104	123	169	201	221	239	216	121	84	47	58	1687
34	92	112	149	173	224	237	260	233	176	133	75	73	1936
35	93	109	156	171	220	241	264	238	180	140	70	77	1959
36	81	99	139	163	198	196	223	208	167	126	63	65	1708
37	83	107	136	167	227	245	266	231	167	131	72	65	1900
38	94	109	155	179	199	211	225	215	165	123	78	78	1832
39	97	113	161	180	228	230	241	226	174	134	78	80	1941
40	73	85	102	116	155	169	202	180	145	112	62	60	1461
41	64	76	89	116	158	188	213	184	145	111	62	52	1458
42	44	71	105	131	186	189	206	186	133	92	54	32	1432
43	103	118	141	160	201	203	234	218	166	140	85	91	1860
44	103	120	135	168	212	226	247	223	166	141	87	90	1918
45	99	118	143	160	202	199	218	204	163	138	87	88	1819
46	83	105	137	156	199	215	244	220	180	133	72	59	1803
47	93	118	140	165	206	203	226	216	182	154	95	84	1885
48	81	106	126	161	204	222	251	225	168	139	74	67	1824

Table 3. Degree-days below 18.0°C

Weather Stn	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Total
1	524	382	368	255	159	83	37	36	88	221	362	464	2983
2	748	545	450	268	128	41	11	19	102	296	493	645	3751
3	860	642	584	380	236	122	47	64	193	391	617	770	4910
4	931	681	613	411	268	156	98	127	247	410	625	803	5376
5	664	505	443	278	144	52	13	19	94	279	467	593	3556
6	479	379	378	277	180	91	39	41	114	248	362	438	3030
7	463	374	382	288	197	113	64	66	124	251	360	427	3115
8	988	776	701	402	211	92	31	54	187	361	628	847	5283
9	923	713	681	441	265	141	68	98	223	386	620	800	5365
10	1068	829	764	443	245	123	79	108	246	414	705	962	5990
11	1108	851	781	459	248	131	78	108	245	430	719	973	6135
12	876	661	622	392	219	95	32	52	167	327	563	735	4745
13	949	726	645	371	183	71	19	36	155	329	587	793	4868
14	1062	849	740	418	211	71	18	39	174	359	648	902	5496
15	1046	832	730	415	208	68	20	39	175	360	648	890	5434
16	1113	894	800	440	221	84	29	50	196	398	693	955	5876
17	1139	880	806	451	222	91	38	62	206	409	702	971	5982
18	1155	920	825	441	217	88	32	60	208	407	711	995	6062
19	1012	800	733	434	235	101	37	60	196	381	652	873	5509
20	1178	947	854	475	241	91	35	65	217	410	716	1009	6242
21	1137	927	806	434	215	76	21	46	186	382	677	963	5875
22	1094	883	766	428	202	57	13	28	156	339	643	943	5560
23	1126	919	787	444	220	66	18	40	175	357	663	967	5787
24	1155	933	832	457	239	83	24	45	196	389	704	1012	6075
25	1154	948	811	439	219	69	21	43	178	369	676	991	5923
26	820	716	591	341	163	38	6	19	100	262	448	720	4229
27	763	681	585	349	183	51	13	22	101	267	448	665	4132
28	960	827	721	445	235	88	36	61	182	360	568	858	5348
29	896	777	650	374	174	44	10	27	127	306	504	797	4691
30	851	747	645	366	195	66	20	36	140	314	475	733	4593
31	982	863	745	458	238	84	30	56	181	361	576	874	5451
32	766	680	588	355	187	51	12	20	102	272	440	666	4143
33	709	616	520	299	135	27	2	6	61	218	409	615	3622
34	891	783	655	380	176	48	9	31	134	313	487	791	4701
35	874	762	636	368	165	40	8	23	116	289	481	771	4537
36	932	815	698	442	227	72	23	48	169	352	546	838	5165
37	921	800	690	437	235	95	44	73	183	356	529	805	5173
38	908	794	694	475	292	114	53	81	204	376	549	806	5350
39	933	811	677	408	196	59	16	41	150	329	529	837	4993
40	749	699	666	512	366	192	72	91	200	371	486	674	5083
41	666	621	610	479	364	196	79	77	175	322	425	587	4606
42	711	683	645	485	343	183	72	70	182	338	453	640	4811
43	842	745	633	419	229	79	20	37	153	326	497	758	4739
44	809	727	648	450	266	103	28	44	156	323	481	726	4763
45	798	721	635	443	278	128	48	55	162	321	470	705	4768
46	778	719	654	471	295	117	28	37	139	306	456	683	4688
47	743	680	609	440	274	106	29	32	131	292	437	646	4424
48	703	674	634	481	328	152	45	45	140	297	425	612	4540

Table 4. Greatest snowfall in 24 hours (cm)

Weather Stn	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Year
1	45.7	45.7	30.5	15.2	5.1	0.0	0.0	0.0	0.0	5.1	35.6	33.0	45.7
2	33.8	10.7	16.8	2.8	T	0.0	T	0.0	T	2.8	30.2	23.9	33.8
3	32.3	23.6	17.8	18.5	6.6	T	T	0.0	3.3	10.2	38.1	31.0	38.1
4	29.2	22.9	19.8	21.8	9.4	0.5	T	T	9.1	22.1	26.9	29.0	29.0
5	19.1	30.5	33.5	5.1	0.0	0.0	0.0	0.0	0.0	12.7	19.8	45.7	45.7
6	29.7	18.3	25.9	3.6	T	0.0	0.0	0.0	0.0	0.3	22.1	31.2	31.2
7	29.2	22.4	21.3	5.1	T	0.0	0.0	0.0	T	T	16.0	34.8	34.8
8*	16.5	17.5	18.0	17.3	15.5	0.0	0.0	0.0	7.6	20.3	18.8	35.1	35.1
9	25.4	27.7	24.1	45.7	48.3	24.9	0.3	6.1	22.9	29.7	35.6	21.8	48.3
10*	20.3	19.1	21.1	22.6	12.8	T	0.0	0.0	7.6	31.5	15.7	16.8	31.5
11	21.8	21.3	22.1	15.7	17.5	T	0.0	19.3	12.7	36.3	21.3	23.4	36.3
12	18.8	24.4	33.5	52.6	32.5	10.9	T	3.8	55.1	35.8	37.8	21.6	55.1
13	26.4	27.9	33.8	25.4	14.0	1.5	0.0	0.0	26.2	21.6	26.7	22.9	33.8
14	15.5	24.9	15.7	35.1	16.8	T	T	0.0	11.7	29.0	18.0	18.8	35.1
15	16.8	20.8	16.3	24.1	11.2	T	0.0	0.0	27.2	18.3	14.5	13.2	27.2
16	14.0	19.1	25.4	23.2	19.8	7.6	T	0.0	21.6	21.3	23.9	14.2	25.4
17	25.4	15.2	15.2	25.4	19.1	T	0.0	0.0	10.2	27.9	20.3	22.9	27.9
18	15.5	30.0	26.9	19.1	18.5	T	T	0.0	7.1	28.4	19.1	16.3	30.0
19	13.7	22.1	33.5	22.9	20.1	5.1	0.0	0.0	12.7	17.8	22.9	18.3	33.5
20	24.9	43.2	21.8	23.6	9.1	T	0.0	0.0	13.2	26.4	24.1	19.1	43.2
21	21.0	40.6	30.5	38.1	13.0	0.0	0.0	0.0	2.5	25.4	28.2	25.4	40.6
22	35.6	25.4	45.7	25.4	22.9	T	0.0	0.0	7.6	15.2	40.9	38.1	45.7
23	22.4	18.8	25.4	53.8	11.7	0.0	0.0	0.0	12.2	21.8	18.8	16.5	53.8
24	17.8	65.0	18.5	20.1	13.2	T	0.0	0.0	3.3	40.6	19.3	25.4	65.0
25	19.1	23.6	35.6	21.3	21.1	0.3	0.0	0.0	1.8	24.6	27.7	21.6	35.6
26	51.8	47.5	45.0	30.5	7.1	0.0	0.0	0.0	2.5	29.0	40.6	31.8	51.8
27	32.5	30.0	27.4	21.8	5.8	0.0	0.0	0.0	T	15.7	40.6	57.0	57.0
28	26.0	26.2	26.7	27.7	10.2	0.0	0.0	0.0	2.0	11.4	27.9	20.3	27.9
29	38.6	39.6	40.6	26.7	15.0	T	0.0	T	1.5	15.5	25.4	30.4	40.6
30	66.0	40.6	55.9	23.4	15.2	0.0	0.0	0.0	2.5	15.2	27.9	30.5	66.0
31	37.0	37.8	34.0	33.5	9.9	T	0.0	0.0	1.8	17.0	21.8	27.2	37.8
32	36.8	39.9	32.3	26.7	2.3	T	0.0	0.0	T	7.4	33.5	28.2	39.9
33	23.9	36.8	22.4	14.2	0.5	T	0.0	0.0	T	2.4	34.8	32.3	36.8
34	71.1	38.1	38.1	27.9	15.2	0.0	0.0	0.0	0.8	29.2	50.8	36.3	71.1
35	32.8	39.4	43.2	25.7	21.8	0.0	0.0	0.0	6.1	14.2	30.5	37.8	43.2
36	32.3	29.2	43.9	33.0	7.1	0.3	0.0	0.0	T	17.3	30.5	35.6	43.9
37*	40.3	31.2	33.0	27.7	16.3	T	0.0	0.0	T	24.4	37.8	34.8	40.3
38	45.7	55.9	61.0	30.5	10.2	T	0.0	0.0	T	25.4	45.7	45.7	61.0
39	38.1	40.6	41.9	43.7	12.7	0.0	0.0	0.0	0.0	10.2	41.1	48.3	48.3
40	35.2	47.8	41.4	37.8	16.5	21.8	T	T	5.1	20.8	43.8	45.7	47.8
41	38.4	54.9	45.7	31.6	25.4	13.5	T	0.0	0.3	19.8	25.3	49.3	54.9
42	56.1	41.7	33.0	21.1	14.0	2.5	0.0	0.0	0.3	12.7	16.5	35.3	56.1
43	36.1	40.6	34.8	26.4	15.2	0.0	0.0	0.0	T	11.4	35.1	78.0	78.0
44	40.6	76.2	40.6	45.7	21.6	1.3	0.0	0.0	T	22.4	31.0	38.1	76.2
45	42.4	34.8	40.1	26.2	10.2	0.0	T	0.0	0.0	19.8	21.3	58.2	58.2
46	47.2	47.5	33.5	38.1	13.2	T	0.0	0.0	T	21.6	30.5	32.0	47.5
47*	43.7	47.2	24.6	28.4	26.9	T	0.0	0.0	T	38.6	20.3	47.5	47.5
48	44.5	45.2	37.3	29.2	24.9	1.0	0.0	0.0	T	15.7	21.6	58.7	58.7

*Records with less than 25 years

Table 5. Mean wind speed (km/h) and prevailing direction

Weather Stn	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Annual
1	14.0	9.4	7.8	6.9	6.1	4.9	4.9	4.5	5.5	6.0	9.5	12.8	7.7
	NE	N	N	S	S	S	S	S	S	S	N	N	S
2	11.8	11.5	13.4	13.2	12.3	11.8	10.5	10.0	10.2	12.1	13.1	13.9	12.0
	E	E	E	W	W	W	W	W	E	E	E	E	E
3	8.5	9.0	10.0	12.1	11.0	11.1	10.5	9.9	9.3	10.4	9.4	8.6	10.0
	S	S	S	S	S	S	S	S	S	S	S	S	S
4	11.4	11.9	11.9	11.7	10.8	9.9	8.7	8.3	9.2	12.5	12.2	12.1	10.9
	S	S	S	S	S	S	S	S	S	S	S	S	S
5	5.9	4.8	6.0	6.8	6.3	7.0	5.8	5.4	4.8	4.3	4.4	4.8	5.5
	N	N	N	S	S	S	N	N	N	N	N	S	N
6	12.2	12.4	13.5	13.3	11.8	11.5	11.4	10.6	10.6	11.2	12.2	13.0	12.0
	E	E	E	E	E	E	E	E	E	E	E	E	E
7	12.5	12.1	12.5	12.1	11.1	10.5	9.5	9.2	9.1	10.0	11.4	12.7	11.1
	W	W	W	W	W	SE	SE	SE	W	W	W	W	W
8	13.2	12.6	13.4	16.0	14.9	13.9	12.3	12.1	12.5	14.1	13.6	13.6	13.5
	NW	NW	NW	NW	NW	NW	NW	NW	NW	SW	S	SW	NW
9	16.2	15.8	16.4	18.1	18.2	17.0	14.9	14.4	15.8	16.3	15.4	16.1	16.2
	W	S	S	NNW	NNW	NNW	NNW	NNW	NNW	W	W	W	W
10	13.4	13.4	13.4	15.2	15.7	13.6	11.6	11.3	13.0	13.6	12.9	13.1	13.4
	S	S	S	S	SE	W	W	W	S	S	S	S	S
11	11.5	12.3	12.8	14.5	16.8	16.2	14.1	13.6	13.7	14.4	12.0	11.3	13.6
	NW	NW	NW	W	W	W	W	W	W	W	W	NW	W
12	21.2	21.2	21.0	21.3	20.4	20.0	16.9	16.8	18.4	22.5	22.4	23.1	20.4
	W	W	W	W	W	W	W	W	W	W	W	W	W
13	15.3	15.2	16.2	18.1	17.3	16.1	14.4	14.5	15.7	17.3	16.7	16.8	16.1
	SW	SW	SW	SW	SW	SW	SW	SW	SW	SW	SW	SW	SW
14	21.5	21.0	20.5	20.8	20.8	19.1	17.8	17.9	19.7	20.4	20.5	21.0	20.1
	NW	NW	NW	E	E	W	NW	E	NW	NW	NW	SW	NW
15	21.6	21.2	21.2	21.3	21.4	19.8	17.5	17.4	20.3	20.9	21.0	21.8	20.5
	WNW	WNW	WNW	SE	SE	W	W	W	W	WNW	WNW	WNW	WNW
16	21.8	21.6	22.0	22.6	22.1	19.9	17.7	18.1	20.4	20.5	20.9	21.7	20.8
	SE	SE	SE	SE	SE	SE	SE	SE	SE	SE	SE	SE	SE
17	14.9	15.5	15.2	16.8	16.9	15.8	14.0	14.1	15.0	16.3	14.8	15.2	15.4
	W	SE	SE	SE	SE	NW	NW	SE	NW	NW	SE	W	SE
18	16.8	16.4	17.5	19.0	19.4	18.2	16.7	16.5	18.1	18.0	16.9	16.8	17.5
	WNW	SW	SE	SE	SE	WNW	W	WNW	WNW	S	WNW	WNW	WNW
19	25.1	24.4	23.4	23.3	22.9	21.7	19.4	19.6	22.1	23.6	23.7	25.1	22.9
	W	W	W	W	W	W	W	W	W	W	W	W	W
20	17.3	16.7	17.5	18.3	19.2	17.8	16.0	15.6	17.8	18.6	18.0	17.3	17.5
	NW	NW	NW	S	S	S	W	S	S	S	NW	NW	NW
21	18.2	17.6	18.1	19.0	19.4	17.9	15.6	15.4	17.6	19.0	17.9	17.3	17.8
	NW	NW	NW	NE	NW	NW	NW	NW	NW	NW	NW	NW	NW
22	13.5	12.6	13.6	13.5	14.0	13.2	11.0	10.5	12.1	13.0	13.7	13.8	12.9
	NW	NW	NW	NW	NW	NW	NW	NW	NW	NW	NW	NW	NW
23	17.9	16.8	17.7	18.7	18.3	16.0	14.4	14.4	16.4	18.0	17.8	17.2	17.0
	NNW	NNW	NNW	N	N	N	W	N	N	W	W	W	NNW
24	18.7	17.5	18.5	21.3	21.8	19.3	17.0	17.1	19.1	19.9	19.4	18.4	19.0
	NW	NW	NW	NW	E	E	NW	E	NW	NW	NW	NW	NW

Table 5. Mean wind speed (km/h) and prevailing direction (concluded)

Weather Stn	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Annual
25	18.6	18.1	19.3	20.9	20.2	18.1	16.0	16.4	18.5	19.6	19.4	18.6	18.6
	S	S	S	S	S	S	S	S	S	S	S	S	S
26	14.0	13.4	13.4	14.1	14.2	14.3	13.6	13.7	15.4	17.0	16.2	12.9	14.4
	W	NW	NW	NW	NW	SW	NW	NW	SW	NW	NW	W	NW
27	19.7	18.4	18.9	18.4	15.9	13.5	11.8	11.5	12.9	14.7	17.6	18.4	16.0
	W	W	E	E	E	S	SSW	W	E	W	WSW	WSW	W
28	15.1	15.4	16.3	16.4	15.1	13.8	12.9	12.5	13.4	14.3	15.6	14.8	14.6
	N	N	N	N	SW	SW	SW	SW	SW	SW	W	E	SW
29	16.2	16.2	16.7	16.8	14.8	13.2	11.8	11.5	12.8	14.1	15.2	15.5	14.6
	WNW	WNW	E	E	SW	SW	SW	SW	W	E	E	WNW	WNW
30	12.8	11.8	13.5	13.8	11.2	10.0	8.7	7.9	8.9	10.3	11.6	11.6	11.0
	W	WNW	WNW	WNW	WNW	WNW	W	W	W	W	W	WSW	W
31	21.0	21.8	21.4	21.7	21.1	20.1	18.8	17.9	19.1	20.4	21.5	21.0	20.5
	N	N	N	N	N	SW	SW	SW	S	S	S	N	N
32	18.4	17.6	17.6	17.3	14.9	13.4	12.5	12.3	13.0	14.1	16.6	17.0	15.4
	WSW	N	N	N	N	N	N	N	N	W	W	W	N
33	20.0	19.9	20.6	19.7	17.2	14.8	12.9	12.5	13.7	15.7	18.4	18.9	17.0
	WSW	SW	WNW	SSW	SSW	SSW	SW	SW	SSW	SSW	SSW	SW	SSW
34	11.5	12.0	12.4	11.8	10.6	9.2	8.2	7.9	8.5	9.9	10.3	10.6	10.2
	W	W	W	W	W	W	W	W	W	W	W	W	W
35	18.3	17.9	17.9	16.9	15.3	14.5	13.1	12.2	13.1	14.8	16.6	16.8	15.6
	WSW	WSW	WSW	W	SW	SW	SW	SW	SW	W	W	W	WSW
36	18.9	18.9	18.0	16.6	16.5	14.5	12.8	12.9	13.4	15.0	16.2	17.7	16.0
	WSW	WSW	ENE	ENE	ENE	WSW	WSW	WSW	WSW	WSW	WSW	WSW	WSW
37	11.5	12.0	12.4	11.8	10.6	9.2	8.2	7.9	8.5	9.9	10.3	10.6	10.7
	W	W	W	W	W	W	W	W	W	W	W	W	W
38	15.7	15.8	16.1	14.7	13.5	13.1	12.5	12.0	12.3	14.4	14.6	15.0	14.1
	S	S	S	N	N	S	S	S	S	S	S	S	S
39	10.1	10.6	11.9	12.1	11.1	9.7	9.0	8.5	8.6	10.0	11.0	11.2	10.3
	SW	NE	NE	NE	NE	SW	SW	SW	NE	NE	NE	NE	NE
40	24.4	23.9	23.4	21.6	19.7	18.7	17.3	17.2	18.9	20.6	21.8	22.8	20.9
	W	W	W	NNW	W	SW	SW	WSW	W	WSW	W	W	W
41	27.5	27.5	26.9	24.4	22.9	22.2	21.4	21.2	22.1	23.8	25.2	26.8	24.3
	W	W	W	WSW	WSW	WSW	WSW	WSW	WSW	WSW	W	W	WSW
42	19.3	18.3	16.9	15.5	13.9	11.9	11.1	12.7	13.9	14.8	16.9	18.5	15.3
	W	W	ENE	WSW	WSW	WSW	WSW	WSW	WSW	W	W	W	W
43	14.6	14.8	16.0	14.8	14.7	13.6	12.3	11.6	12.0	13.0	13.4	14.3	13.8
	WNW	WNW	WNW	WNW	SSW	SSW	SSW	SSW	SSW	SSW	WNW	WNW	WNW
44	20.3	19.8	20.5	19.0	18.1	16.9	15.2	15.2	16.2	17.7	18.7	19.9	18.1
	W	WSW	WSW	WSW	WSW	SW	WSW	WSW	WSW	WSW	WSW	WSW	WSW
45	20.6	20.2	21.0	19.1	18.3	17.3	15.5	15.0	16.4	18.3	19.8	20.5	18.5
	NW	NW	NW	N	SSW	SSW	S	S	SSW	SSW	NW	NW	S
46	22.1	20.8	21.7	19.9	18.9	18.0	16.1	16.0	17.2	19.1	20.4	21.5	19.3
	W	W	W	N	WSW	WSW	WSW	WSW	WSW	W	W	W	W
47	20.2	19.7	20.7	19.2	18.5	17.3	15.9	15.4	15.7	17.2	18.5	19.8	18.2
	WNW	WNW	N	N	S	S	SSW	S	SSW	SSW	N	NW	SSW
48	24.4	23.8	24.1	22.2	21.1	20.0	18.6	18.4	19.3	21.3	22.9	23.8	21.7
	W	W	N	N	SSW	SW	SSW	SW	SW	SW	W	W	SW

Appendix B

Sun path charts

An appropriate sun path chart corresponding to a site's latitude can help a grower determine the amount of solar radiation reaching an existing greenhouse or a proposed greenhouse location. Sun path charts for latitudes of 43°, 49°, 53°, and 60° have been provided (Figs. 20, 21, 22, and 23, respectively). Trees, buildings, mountains, and so forth that could interfere with the incoming solar radiation should be drawn into the appropriate chart after their angular heights and azimuth bearings (horizontal angles from true south) have been established.

A protractor can be used with a string and a weight (Fig. 18) to measure the angular altitude of obstructions around a greenhouse. A compass will indicate the horizontal angle from true south. The magnetic south pole must not be used; otherwise the readings on the charts will be incorrect.

By drawing obstructions onto the chart, using their respective angular heights and azimuth bearings, the percentage of the radiation blocked by the obstructions can be read, using the figures in the shaded squares.

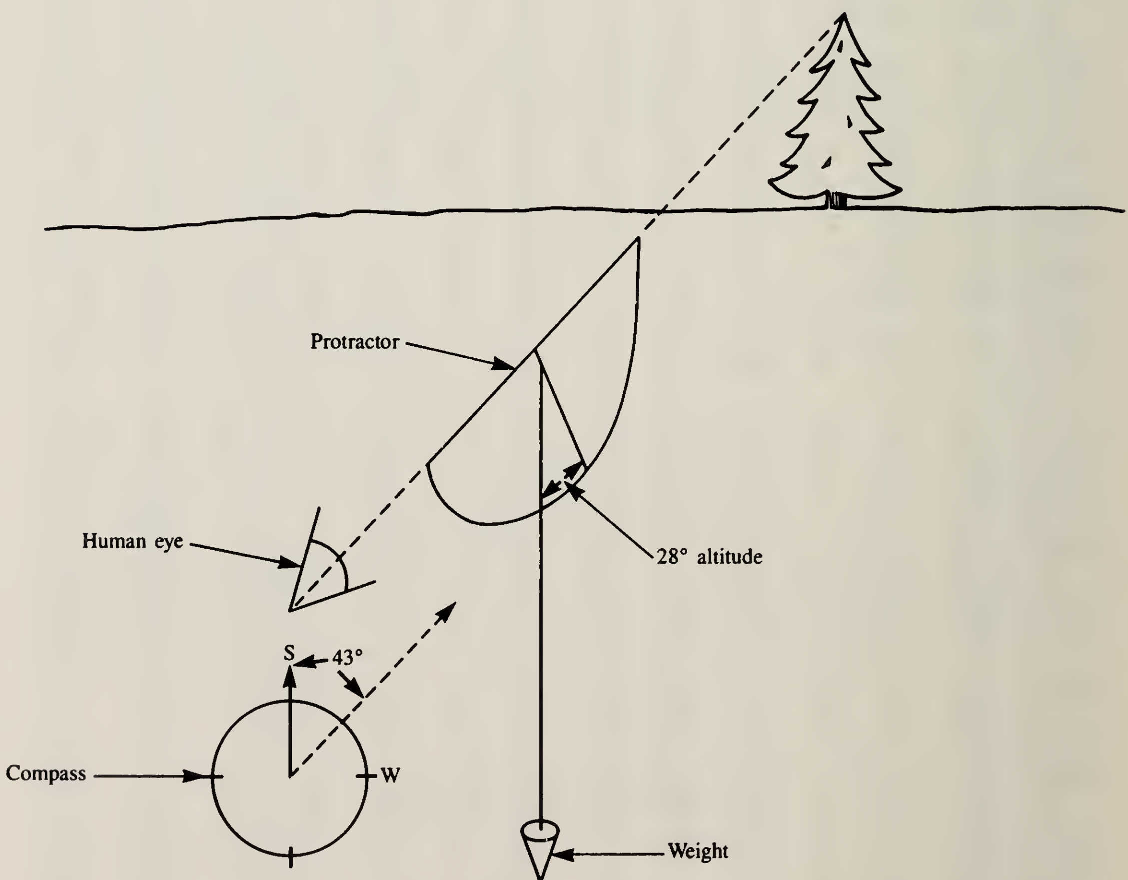

Fig. 18. *A protractor, used to measure the angular altitude of obstructions around a greenhouse.*

Example:

A tree located at 43° west of due south (horizontal axis) with an altitude (height) of 28° (vertical axis) blocks the direct solar radiation reaching the greenhouse as follows (refer to Fig. 19):

- approximately 9% in December;
- approximately 12% in January and November (including shading of exterior branches);
- approximately 9% in February and October;
- almost 0% during the period March–September.

Since less than 15% of the incoming light in October is blocked out and virtually no shading occurs during the remaining months of the March–October growing season, this site would be suitable for solar heating.

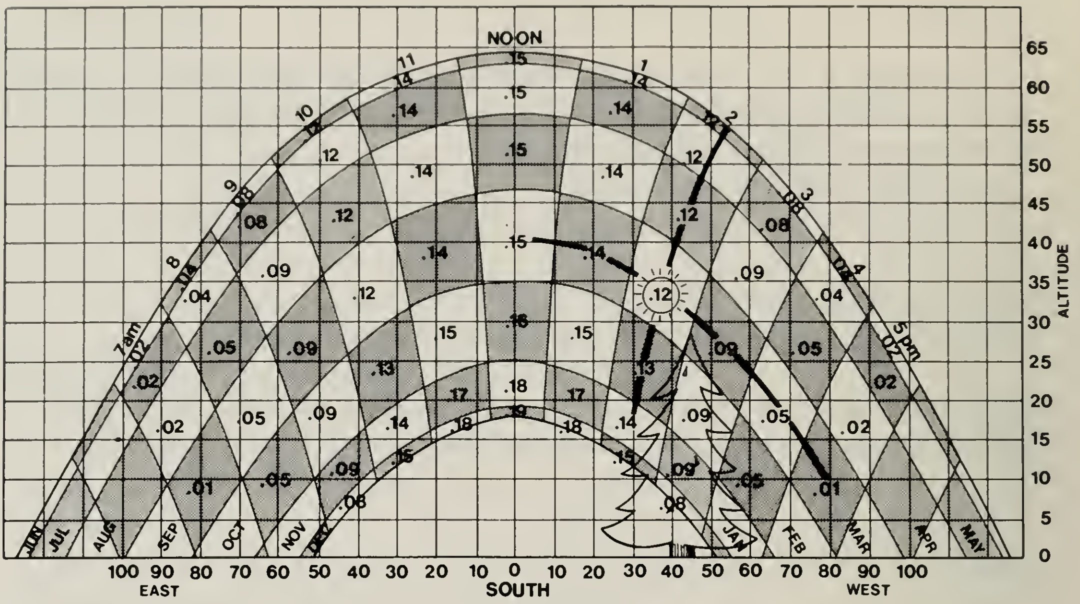

Fig. 19. *Sun path chart 49° north. Hourly fraction of daily total sunshine.*

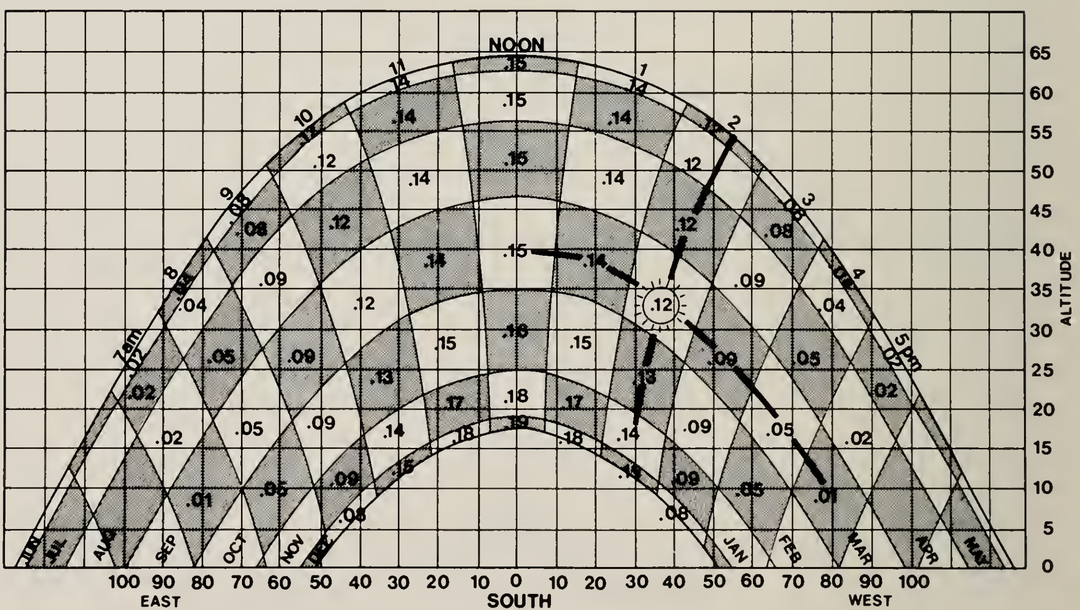

Fig. 20. *Sun path chart 49° north. Hourly fraction of daily total sunshine. The sun path chart records in two dimensions the annual movement of the sun across the sky for a specific latitude. The base line represents a flat horizon. The bottom arch is in the path of the sun at the winter solstice (21 December), the top arch is the summer solstice (21 June).*

Radial lines indicate the time of day (standard time). Time numbers are centered on each square.

The number in each square indicates the fraction of solar energy (under ideal conditions) that occurs during a 1-hour portion, between 30 min., before and after the time indicated, on the 21st day of the month. The example plotted shows that on 21 March/21 September, 12% of the daily total solar energy falling on a vertical surface occurs (under ideal conditions) between 1:30 P.M. and 2:30 P.M., local solar time. In this graph it is averaged, and assumed constant over a month. Local solar time is close to local standard time.

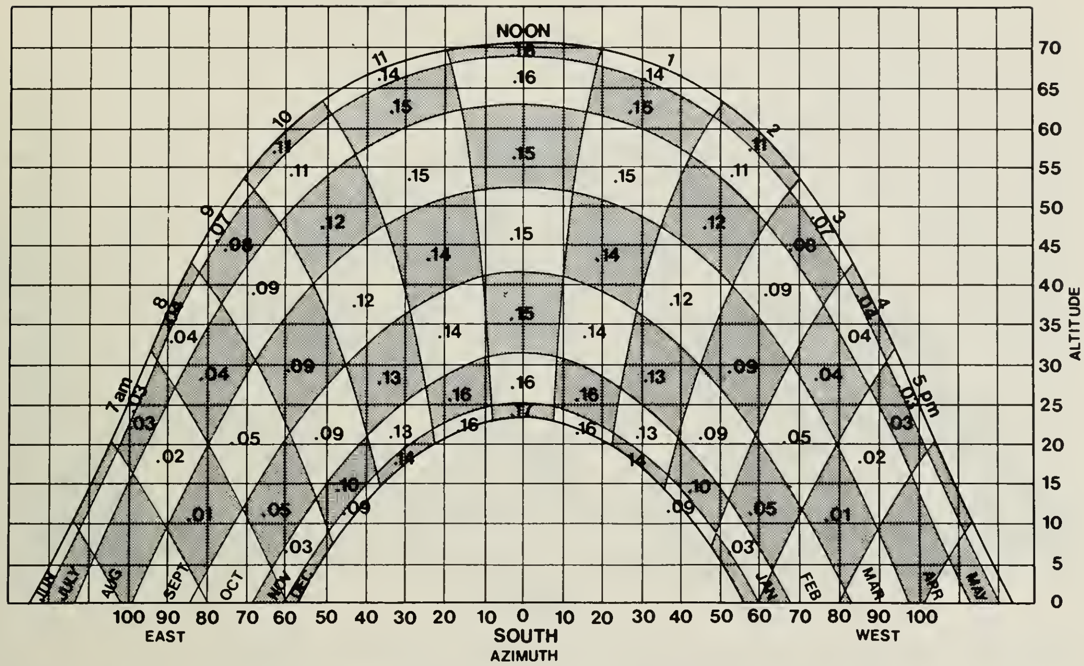

Fig. 21. *Sun path chart 43° north. Hourly fraction of daily total sunshine.*

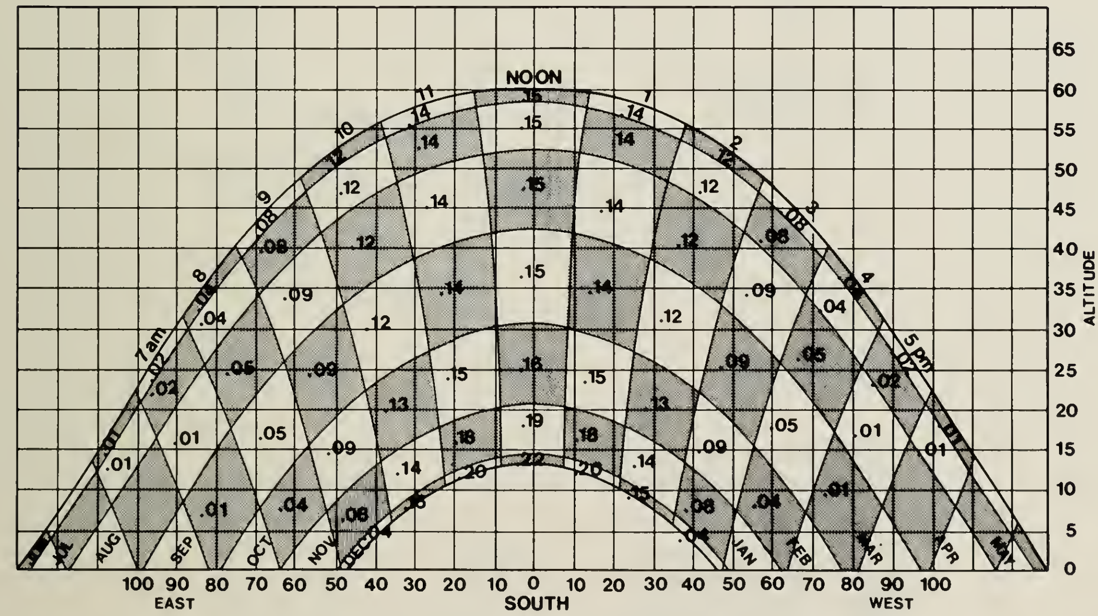

Fig. 22. *Sun path chart 53° north. Hourly fraction of daily total sunshine.*

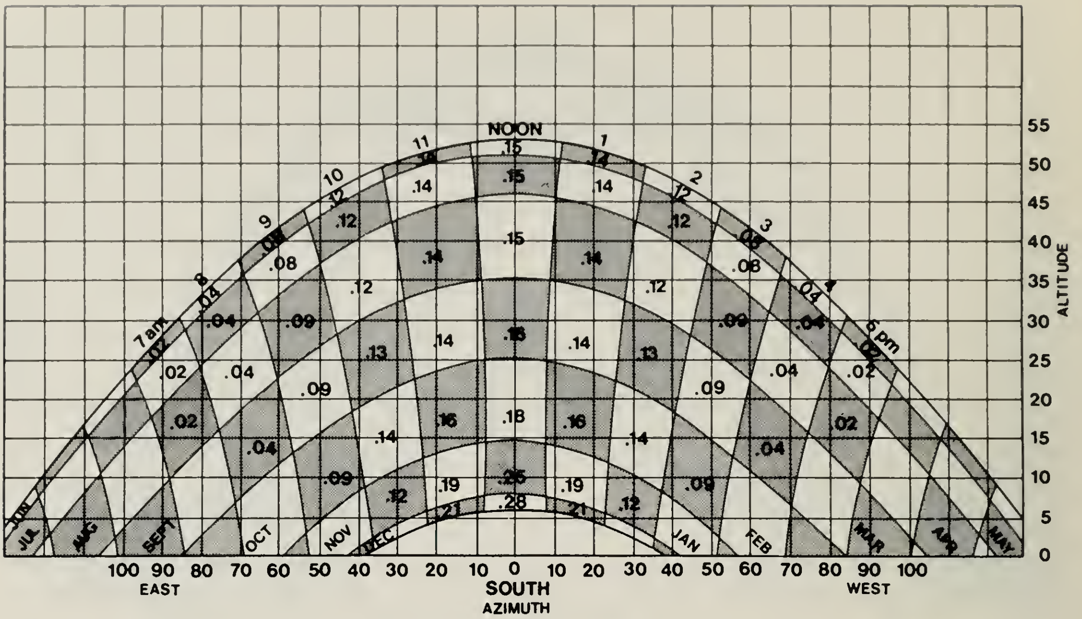

Fig. 23. *Sun path chart 60° north. Hourly fraction of daily total sunshine.*

CONVERSION FACTORS FOR METRIC SYSTEM

Imperial units	Approximate conversion factor	Results in:	
LINEAR			
inch	x 25	millimetre	(mm)
foot	x 30	centimetre	(cm)
yard	x 0.9	metre	(m)
mile	x 1.6	kilometre	(km)
AREA			
square inch	x 6.5	square centimetre	(cm^2)
square foot	x 0.09	square metre	(m^2)
acre	x 0.40	hectare	(ha)
VOLUME			
cubic inch	x 16	cubic centimetre	(cm^3)
cubic foot	x 28	cubic decimetre	(dm^3)
cubic yard	x 0.8	cubic metre	(m^3)
fluid ounce	x 28	millilitre	(mL)
pint	x 0.57	litre	(L)
quart	x 1.1	litre	(L)
gallon	x 4.5	litre	(L)
WEIGHT			
ounce	x 28	gram	(g)
pound	x 0.45	kilogram	(kg)
short ton (2000 lb)	x 0.9	tonne	(t)
TEMPERATURE			
degrees Fahrenheit	(°F-32) x 0.56 or (°F-32) x 5/9	degrees Celsius	(°C)
PRESSURE			
pounds per square inch	x 6.9	kilopascal	(kPa)
POWER			
horsepower	x 746	watt	(W)
	x 0.75	kilowatt	(kW)
SPEED			
feet per second	x 0.30	metres per second	(m/s)
miles per hour	x 1.6	kilometres per hour	(km/h)
AGRICULTURE			
gallons per acre	x 11.23	litres per hectare	(L/ha)
quarts per acre	x 2.8	litres per hectare	(L/ha)
pints per acre	x 1.4	litres per hectare	(L/ha)
fluid ounces per acre	x 70	millilitres per hectare	(mL/ha)
tons per acre	x 2.24	tonnes per hectare	(t/ha)
pounds per acre	x 1.12	kilograms per hectare	(kg/ha)
ounces per acre	x 70	grams per hectare	(g/ha)
plants per acre	x 2.47	plants per hectare	(plants/ha)

DATE DUE
DATE DE RETOUR

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